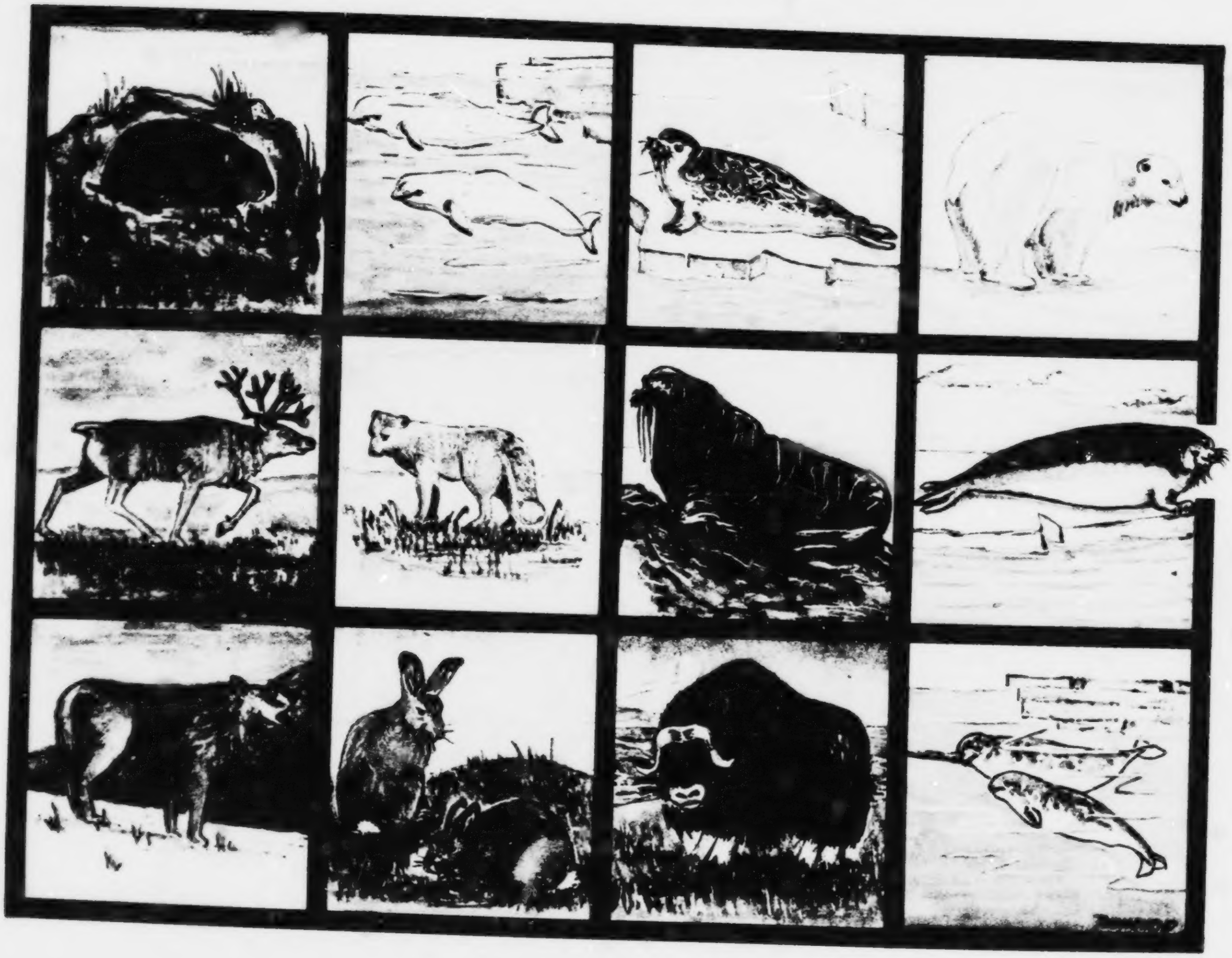
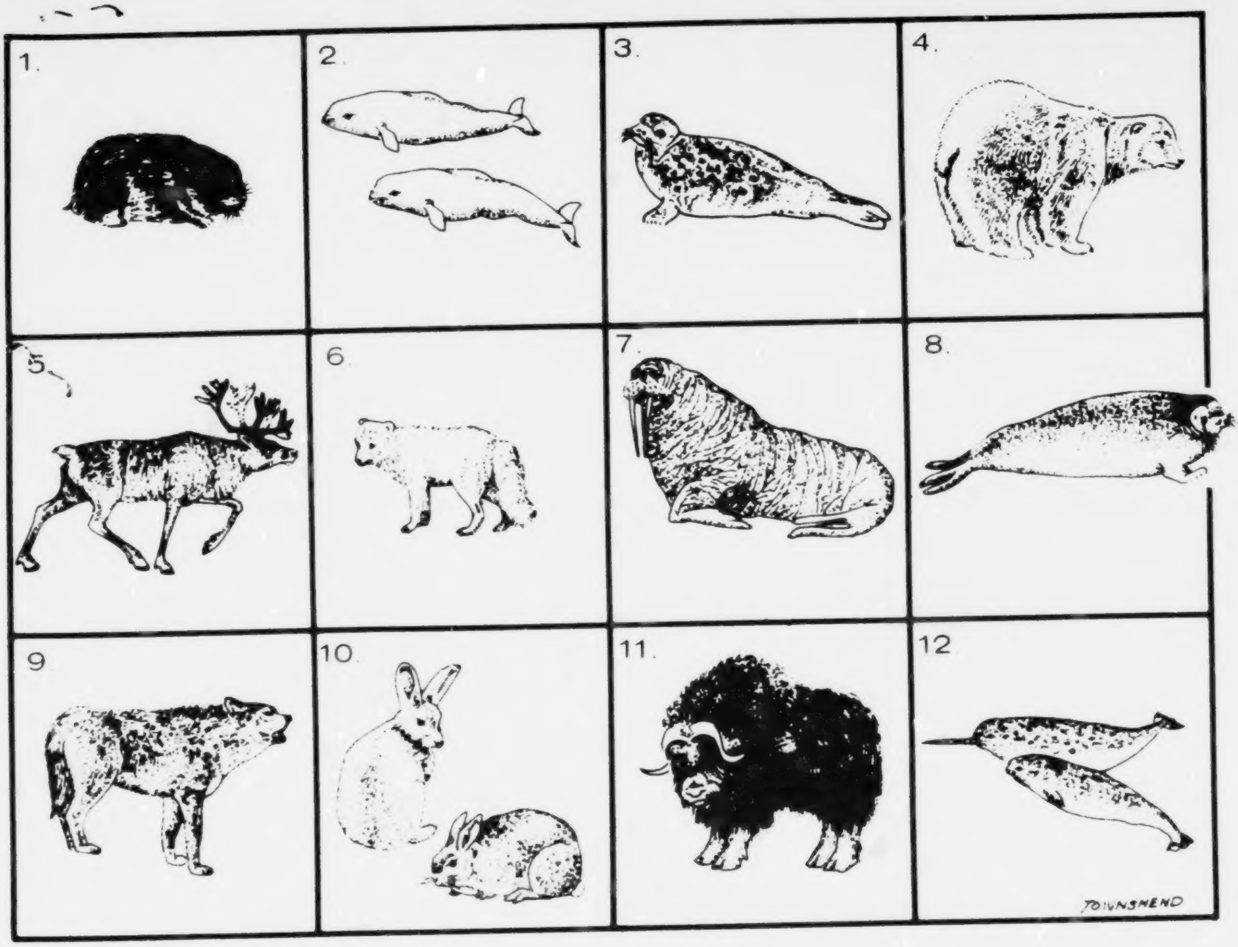
# PROCEEDINGS
# OF THE SIXTH
# ARCTIC MARINE OILSPILL PROGRAM
# TECHNICAL SEMINAR



JUNE 14-16, 1983

EDMONTON, ALBERTA

# MAMMALS OF THE ARCTIC



| | | |
|---|---|---|
| 1 | LEMMING | *Dicrostonyx groenlandicus* |
| 2 | WHITE WHALE (Beluga) | *Delphinapterus leucas* |
| 3 | RINGED SEAL | *Phoca hispida* |
| 4 | POLAR BEAR | *Ursus maritimus* |
| 5 | CARIBOU | *Rangifer tarandus groenlandicus* |
| 6 | ARCTIC FOX | *Alopex lagopus* |
| 7 | WALRUS | *Odobenus rosmarus* |
| 8 | BEARDED SEAL | *Erignathus barbatus* |
| 9 | WOLF (Grey) | *Canis lupus* |
| 10 | ARCTIC HARE | *Lepus arcticus* |
| 11 | MUSKOX | *Ovibos moschatus* |
| 12 | NARWHAL | *Monodon monoceros* |

- Mammal names follow Banfield (1974). Mammals of Canada
- Graphics by B.A.K. Townshend (E.P.S. Environment Canada)

# PROCEEDINGS OF THE
# ARCTIC MARINE OILSPILL PROGRAM
# TECHNICAL SEMINAR

Seminar Sponsored by the

Environmental Protection Service

Seminar Held June 14-16, 1983

Edmonton, Alberta

Inquiries relating to technical content of papers in this seminar should be directed to the author(s). Inquiries relating to the AMOP program in general should be directed to:

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# SESSION I PHYSICAL BEHAVIOUR

## CANOLA OIL AS A SUBSTITUTE FOR CRUDE OIL IN COLD WATER SPILL TESTS

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### INTRODUCTION

The test and evaluation of oil spill containment and recovery equipment under actual field conditions is often difficult or impossible without the use of oil. Numerous substitutes have been tried including popcorn, oranges, wood chips and many other natural and synthetic materials. Most of these substitutes fail in matching the actual behavior of oil on water, particularly with respect to their recovery using conventional oil skimming equipment. The problem is even more difficult in cold climates, where field tests must account for the effects of very low temperatures and the presence of ice.

The physical properties and behavioral characteristics of Canola oil (also known as rape seed oil) were assessed and compared with Prudhoe Bay crude oil under a variety of conditions. This paper presents a summary of tests conducted in the cold chambers at the University of Alaska, Anchorage. Emphasis was placed on the feasibility of using Canola oil (a nontoxic vegetable oil) for testing containment and recovery equipment in cold climates. And, since Canola oil has shown promise for use under ice and with weir skimmers (Quam, 1978; Tsang and Chen, 1978; Tsang et al., 1978), this effort focused on the potential applications for Canola oil involving oleophilic/sorbent recovery systems with or without ice.

The Canola oil used during these laboratory tests was donated by Narp Processors Ltd., of Sexsmith, Alberta, while the Prudhoe Bay crude oil was obtained through the Alaskan Beaufort Sea Oilspill Response Body (ABSORB). The Prudhoe Bay crude oil used during these tests had been stored in a 55-gallon (250 L) drum for approximately 2 years, having been collected initially as fresh hot oil.

### CANOLA AND PRUDHOE BAY CRUDE OIL PROPERTIES

Several physical properties, including specific gravity, viscosity, and interfacial tension, were determined for Canola oil and Prudhoe Bay crude oil at controlled temperatures ranging from -23°C to 27°C. In addition, evaporation rates for the oils were measured at temperatures of -32°C and -7°C.

#### Specific Gravity Measurements

The specific gravities of the Prudhoe Bay crude and Canola oils were measured over the temperature range noted above using standard petroleum hydrometers. The fluid temperature before and after each measurement was obtained using a 0.01 cm diameter Type T thermocouple and a Fluke Model 2190A Digital Thermometer. Fluid temperatures were controlled utilizing cold chambers at the University of Alaska, Anchorage.

As shown in Figure 1, the specific gravity versus temperature relationships for the Canola oil and the Prudhoe Bay crude oil tested were found to vary in a linear fashion. The specific gravity of the Canola oil was approximately 4% higher than that of the crude oil over the indicated temperature range.

#### Viscosity Measurements

The viscosities of the Canola and Prudhoe Bay crude oils were measured at temperatures from -18°C to 27°C using a Haake Falling Ball Viscometer. Oil temperatures were controlled with a cooled 50% glycol and water solution which was circulated around the viscometer measurement tube. The oil temperatures were measured before and after each test using a 0.01 cm Type T thermocouple and a Fluke Model 2190A Digital Thermometer. At least five runs were made for each fluid at each temperature, with a series rejected if the resulting data for a given temperature had a scatter of more than 4%.

Figure 2 contains plots of the measured viscosities for Canola oil, Prudhoe Bay crude oil and Norman Wells crude oil. The Prudhoe Bay and Norman Wells crude oil viscosity data represented by dashed lines were obtained from Figure 3-18 of the ABSORB Oilspill Contingency Plan (1980). The Canola and Prudhoe Bay crude oil viscosity data shown

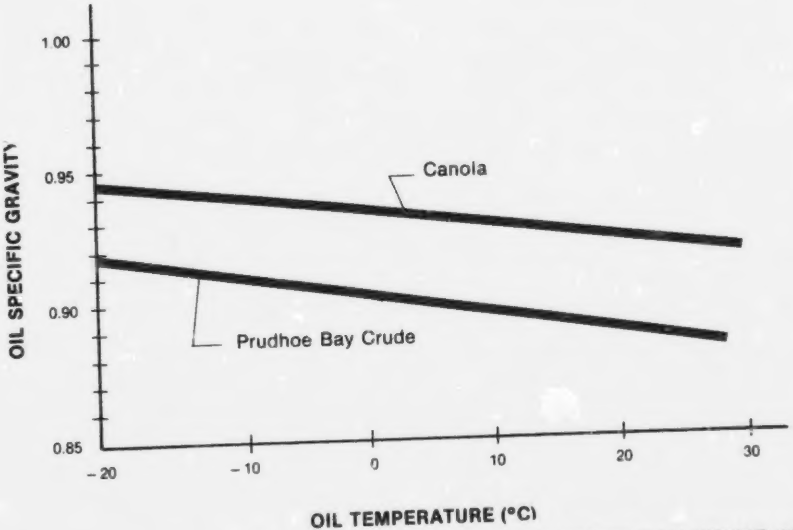
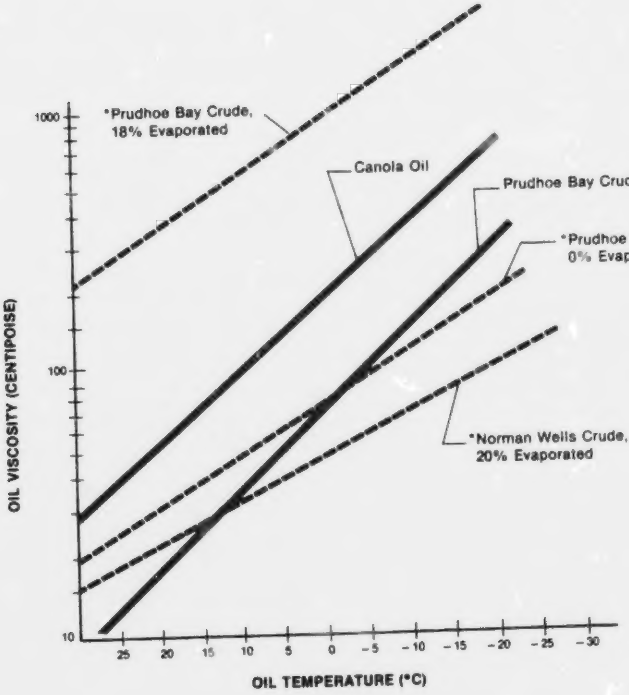


FIGURE 1 SPECIFIC GRAVITY OF CANOLA AND PRUDHOE BAY CRUDE OIL VERSUS TEMPERATURE



*ABSORB OIL SPILL CONTINGENCY PLAN, Figure 3-18.

FIGURE 2 CANOLA VISCOSITY VERSUS CRUDE OIL VISCOSITY

as solid lines are those determined in this experiment. Because of its relevance to oil spill cleanup considerations, the pour point of the Canola oil was examined and was estimated to be -26°C. As a comparison, the pour point for Prudhoe Bay crude oil, approximately 10% evaporated, is -25°C (ABSORB, 1980).

### Interfacial Tension

Using ASTM D-971 procedures, the interfacial tension between the Canola [illegible] and distilled water at 25°C was found to be 11.1 dynes/cm, while the interfacial tension between Prudhoe Bay crude oi[illegible]d distilled water was measured as 26.8 dynes/cm.

### Evaporation Rates

Canola and Prudhoe Bay crude oil samples were placed in 8.7 cm diameter plastic containers to an average depth of 1 cm, with the oil surfaces within 3 mm of the top of the containers. The samples were subjected to air temperatures of -7°C and -32°C; the wind speed was measured 1 cm directly above each sample with a HWA-102 Constant Temperature Hot Wire Anemometer. The wind speed, although variable, averaged 2 m/s, with excursions from 0.4 to 4 m/s. The weight loss for each sample was determined during the 10-day tests using a Fisher/Ainsworth Model LC-100 Scale.

There was no measurable weight loss for the Canola oil during the test period. The results of the evaporation tests for the crude oil are shown in Figure 3. The variation in wind speed from sample to sample (0.4 to 4 m/s) during this test did not strongly affect the evaporation rates compared to the temperature effects. As a result, the evaporation rates shown in Figure 3 are considered to represent an average of these wind speeds (2 m/s).

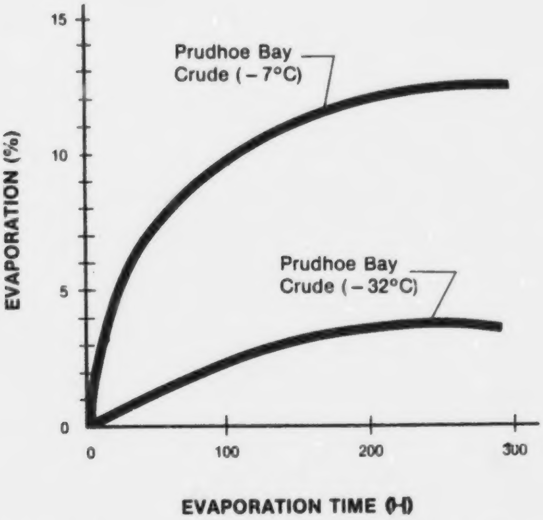


FIGURE 3 MEASURED EVAPORATION OF PRUDHOE BAY CRUDE OIL VERSUS TIME AND TEMPERATURE (Air Speed Variable at ≈2 m/s)

## OIL BEHAVIOR TESTS

The behavior of Canola oil and crude oil in the presence of rope mop fibres, sorbent pads, and ice was examined. All tests were conducted with prepared seawater mixtures (approximately 35 parts per thousand), polypropylene fibres removed from a section of ABSORB's ARCAT* skimming system, small squares of nonwoven polypropylene micro-fibre (3M Type 151 pads, 4.8 mm thick), and ice prepared from the same seawater mixtures. (The ARCAT is a 65-ft self-propelled catamaran skimming vessel utilizing rope mops to recover spilled oil. The ARCAT is stationed at Prudhoe Bay, Alaska.) The objectives were to assess the oleophilic properties of each of these media (mop fibres, pads and ice) while noting the rates of oil uptake and release. A simple oil-and-water shake test was also conducted under warm and cold conditions, to compare the tendencies for Canola oil and crude oil to emulsify with seawater.

### Rope Mop Fibre Adhesion

**Procedures.** Identical tests were carried out with Canola oil and Prudhoe Bay crude oil under four different air/seawater conditions:

| No. 1 | No. 2 | No. 3 | No. 4 |
|---|---|---|---|
| Warm Water<br>(16°C to 20°C) | Cold Water<br>(-1°C to +1°C) | Cold Water<br>(-1°C to +1°C) | Cold Water<br>(-1°C to +1°C) |
| Warm Air<br>(24°C to 26°C) | Warm Air<br>(24°C to 26°C) | Cold Air<br>(-4°C to 0°C) | Very Cold Air<br>(-34°C to -32°C) |

Tests in Conditions 3 and 4 were completed prior to any accumulation of ice at the oil/water interface.

Small rope mop bundles were made by cutting approximately 1 g of fibre from a 12 in. (30.5 cm) rope mop. The fibres of each bundle were wired together at one end and weighed prior to each test.

Aluminum pans with seawater 8 to 10 cm deep were prepared with crude oil and with Canola oil for each of the four conditions described above. A sufficient volume of oil was used in each case to create a layer approximately 4 mm thick. The bundles of rope mop fibre were then dipped in the oil for a total exposure of 15 seconds, the approximate time a zero relative velocity (ZRV) mop system 10 m long at the surface might be in contact with oil while moving at 1.5 knots. The fibre bundles were then lifted above the surface, allowed to drain for 5 seconds, and squeezed between two plastic rollers that were spring-loaded for constant pressure. The bundles and the pan of water and oil were weighed before and after each dip/squeeze. The average quantities of oil picked up, squeezed off, and remaining on the bundles could then be determined.

**Findings.** In all tests, under each of the four conditions described above, the rope mop fibres were observed to reach an apparent saturation level within a few seconds. The volumes of oil plus water recovered for crude oil ranged from 1.5 g per dip to approximately 5.5 g per dip, to more than 8 g per dip. Figure 4 illustrates these comparative recovery rates for the two oils showing how the recovered volume in each case increased with decreasing water and air temperatures.

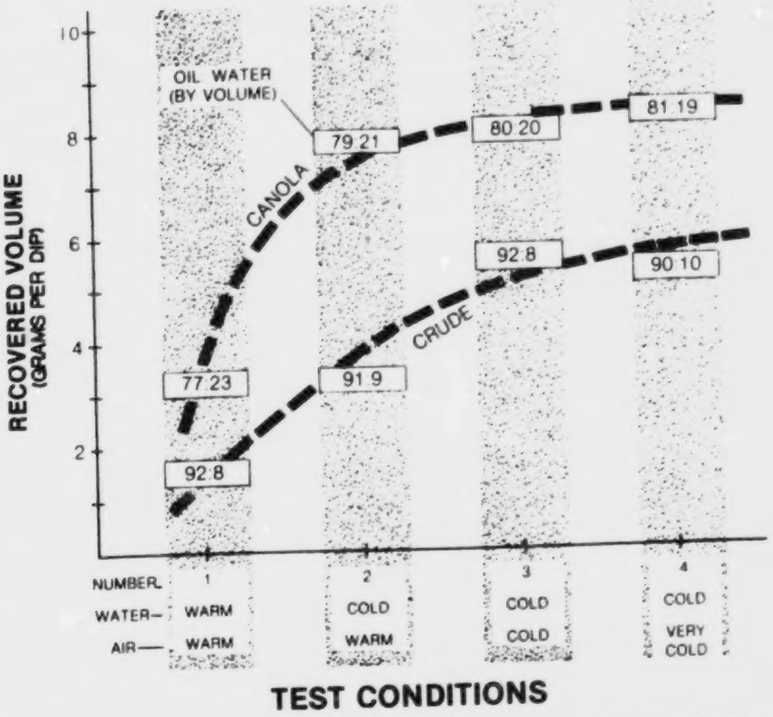


FIGURE 4 ROPE MOP RECOVERY WITH CANOLA AND CRUDE OIL

In the warm air tests (Conditions 1 and 2), the recovered volume of Canola oil per dip was twice as much as it was for crude oil. However, during the cold tests (Conditions 3 and 4), the Canola oil recovery rate was only 40 to 50% greater than that for crude oil. These latter tests are more representative of the actual operating conditions a rope mop skimmer might be subjected to during winter and breakup recovery operations on a cleared (ice-free) pool of oil and water. Should such a field test be conducted using Canola oil, these laboratory (cold-room) experiments suggest that the recovered volumes (for a saturated rope mop) would very likely be 40 to 50% greater than the actual volumes had fresh Prudhoe Bay crude oil been used.

It is also important to consider the percentage of water collected in each of these tests. The oil-to-water ratios for the recovered volumes varied between the two oils, as shown in the boxes of Figure 4. The rope mop fibres picked up between 19 and 23% water when used with Canola oil, while the water uptake with crude oil varied between 8 and 10%. Allowing for the lower water contents found in the crude oil test, these tests suggest that a field test with Canola oil and rope mop fibres would likely involve oil recovery rates that are 30 to 40% greater than the actual oil recovery rates had fresh Prudhoe Bay crude oil been used. These comparisons, of course, depend upon a sufficient thickness of oil being available to saturate the rope mop fibres.

### Sorbent Uptake

**Procedures.** Conditions 1 and 3, involving warm water/warm air and cold water/cold air, were also selected to evaluate the comparative uptakes of Canola oil and crude oil in sorbent pads. Small (5 cm x 5 cm) squares were cut from 3M sorbent sheets (Type 151, 4.8 mm thick) and weighed.

Pans of seawater were prepared as before, with Canola oil and crude oil layers nearly 4 mm thick. The sorbent pads were placed one by one on the oil in each pan (for each of Conditions 1 and 3) for a period of 15 seconds. Each pad was allowed to drain in a vertical position for 5 seconds before it was weighed, and the average volumes recovered per pad were recorded.

It was noted during Condition 1 that the crude oil saturated each pad quickly, while the Canola oil required more than the 15 second exposure time. Data were therefore recorded on the volumes and times to achieve saturation as well.

**Findings.** During test Condition 1 (warm water and warm air), the sorbent pads were put through the dip-and-weigh test without oil to measure the amount of water that might adhere to them. The fact that the 5 cm x 5 cm pads averaged about 0.05 g of water each per dip confirms their hydrophobic properties. The volumes of oil absorbed by the pads in each of the two tests are shown in Figure 5. The dashed lines are provided only to suggest a possible trend in the oil uptake data for the air/water test conditions being examined. During the 15 second exposure tests, only the warm crude oil in Condition 1 was found to penetrate and saturate each pad (requiring 3 seconds). Whether warm or cold, however, crude oil absorption per pad remained about 1 gram higher than with the Canola. The drop in recovered oil at the colder temperatures is consistent with the expected reductions in penetration with increased viscosities.

When the pads were permitted to saturate, however, the absorbed volumes were nearly the same for crude oil and Canola oil, the amounts increasing with the reduced temperatures. Once saturated at the colder temperatures (requiring about 2 minutes), there was a tendency for more oil to adhere to the outer surfaces of the sorbent.

During actual spill cleanup operations, sorbents would normally be exposed to the spilled oil to achieve saturation if possible. The Canola oil and the crude oil had very similar absorption characteristics when used in this mode.

### Ice Adhesion

**Procedures.** Ice adhesion tests were conducted with air and water temperatures at or slightly below 0°C. Canola oil and Prudhoe Bay crude oil were placed on top of seawater in separate containers. Each container had 2 L of seawater and 200 mL of oil, creating a 9 mm oil layer with an area of 231 $cm^2$. Small cubes of sea ice were then placed in each container, using 14 cubes to fill the available surface area.

During each test, the cubes of ice were exposed to the oil for 2 minutes. A wire screen was then used to lift the oiled ice above the surface, where it was allowed to drain for 1 minute. The thickness of the oil layer and the condition of the oiled ice were then noted, and a clean batch of ice was placed in the oil. This procedure was repeated four times with each oil. In separate tests, cubes of sea ice were pushed down through the oiled surface, and the degree of oil adhesion to the ice was noted.

**Findings.** Both the Canola oil and the crude oil had the same tendency to coat the sea ice as it was placed through the oil/water interface of each container. The oil would not stick to any portion of the ice surfaces that remained below the oil/water interface; however, the upper surfaces became coated with both oils and remained coated even after removal from the container.

The volumes of oil removed during each ice lift were identical for both oils. Each lift reduced the oil layer thickness by 1 mm. The estimated surface area of the ice removed during each lift was 840 $cm^2$. Assuming that approximately 80 to 90% of that surface area was contacted by oil upon removal, then the ice surfaces were coated with

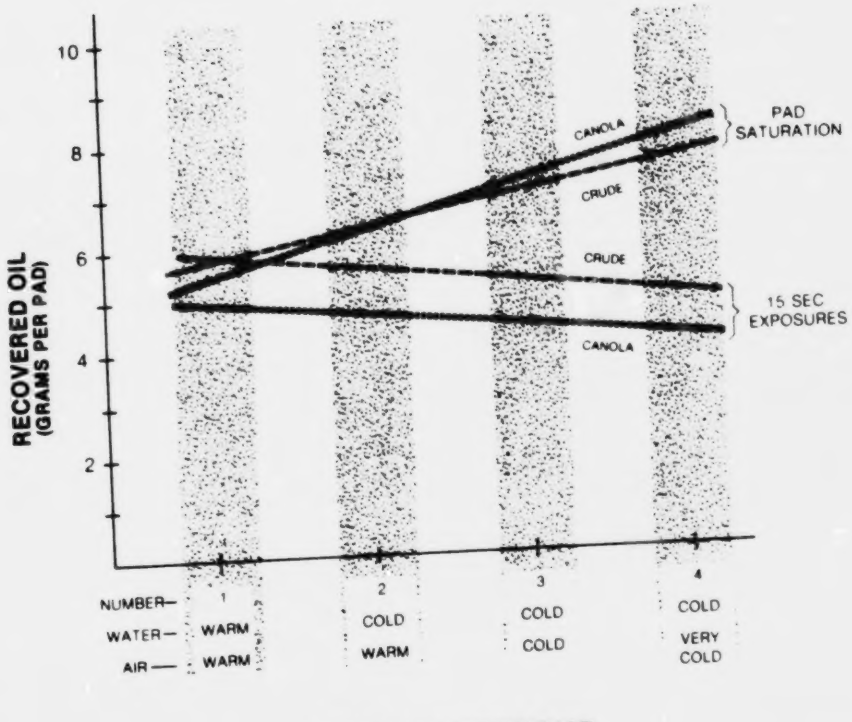


FIGURE 5 SORBENT PAD RECOVERY WITH CANOLA AND CRUDE OIL

an average oil thickness of approximately 0.3 mm. Because of the reduced air temperatures, the oil in each case remained on the ice, with very minor release until disposed of the following day.

During the course of these experiments, it was noted that neither the Canola nor the crude oil would stick to the sea ice when the ice was pushed completely beneath the oil/water interface. The Canola had a slightly greater tendency to stay on a horizontal underside; however, the slightest agitation of the ice would free it from any remaining oil. This lack of oil adherence to submerged sea ice even after surface coating is of significance in the development of improved oil recovery equipment for use in broken ice.

**Emulsification**

**Procedures.** The comparison of tendencies for Canola and Prudhoe Bay oils to become emulsified by agitation was examined under warm (24°C) and cold (0°C) conditions. In each case, 50 mL of Canola oil and 50 mL of crude oil were placed in separate graduated cylinders, each also containing 50 mL of seawater. The cylinders and their contents were held for approximately 1 hour at their respective test temperatures, and then shaken by hand for 60 seconds. Each cylinder then remained undisturbed at its test temperature while the contents were observed and photographed over the next 2 hours.

**Findings.** The shake test under warm (24°C) conditions produced water-in-oil emulsions quite unlike those produced during the cold (0°) test. The results of each test are illustrated in Figure 6.

In the warm test with Canola oil, a small water-in-oil emulsion (about 20 mL) formed immediately after shaking. Canola oil and water gradually separated out of the mixture, with 9 mL of water-in-oil emulsion left after 2 hours. In contrast to this stable emulsion, the warm crude oil took up 45 mL of seawater immediately after shaking (i.e., 95% of the content was water-in-oil emulsion), and about 1.5 hours were required for the clear-water volume to return to 40 mL. The nature and extent of water droplet entrainment within the oil could not be assessed visually because of the crude oil's opacity.

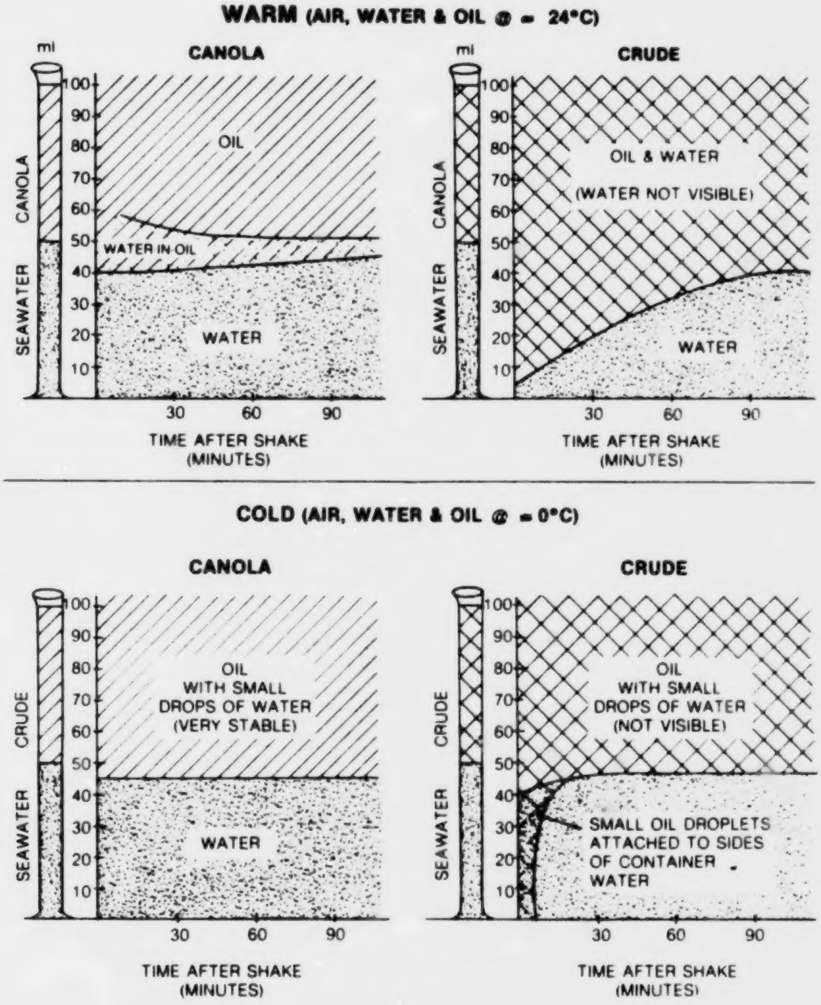


FIGURE 6 EMULSIFICATION TESTS - CANOLA AND CRUDE OIL

During the cold test (0°C), both oils revealed a tendency to avoid emulsification. Some of the crude oil broke into small globules within the water column; however, the majority of these globules quickly rose and recombined with the overlying oil layer. Only a few small globules remained for the first 20 minutes attached to the walls of the cylinder in the water column. Shortly after both cylinders were shaken, it was clear that very little water had been entrained in each of the oils. The Canola oil and the crude oil took on approximately 5 mL (or 10%) of the original water volume as a stable portion of the overlying oil.

## SUMMARY AND CONCLUSIONS

The results of these cold-chamber tests suggest that Canola oil can be used as a viable substitute for crude oil during the field testing of certain types of spill control equipment, with or without the presence of broken ice. Observations made during the laboratory tests can be summarized as follows:

(a) The specific gravity and the viscosity of Canola oil vary linearly with temperature. The variation of its viscosity with temperature suggests that Canola oil represents a "medium weight" oil that is comparable to a lightly weathered Prudhoe Bay crude oil (i.e., about 10% evaporated).

(b) The volume of Canola oil used during a spill test will remain unaffected by the usual influence of evaporation.

(c) Canola oil exhibits an affinity for oleophilic surfaces which is quite similar to that of crude oil. Canola oil's greater viscosity (compared to fresh Prudhoe Bay crude oil) results in a 30 to 40% increase in oil recovery rate with saturated rope mop fibres under Arctic air and water temperatures.

(d) Canola oil penetrates the fibres of sorbent pads at a slightly slower rate than does fresh Prudhoe Bay crude oil; however, saturation of the pads can be accomplished within minutes and the recovered volumes of Canola and crude oil are nearly identical.

(e) Canola oil and Prudhoe Bay crude oil have the same tendency to coat the surface of sea ice drawn up through an oil/water interface. Both oils also showed the same tendency to slide off submerged ice surfaces quite rapidly and completely.

(f) Under cold air, water and oil temperatures (0°C), both the Canola and the crude exhibited similar tendencies for emulsification. Each oil took on approximately 10% of its original volume in water globules which did not settle out for several hours following the original 1 minute shake test.

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# SINKING OF OIL: WATER DENSITY CONSIDERATIONS

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## INTRODUCTION

Historically, the behaviour of oil spills has indicated that under certain environmental conditions, oil sinks below the surface. In 1966, a damaged tanker, ANNE MILDRED BROVIG, released 125,000 barrels of Iranian crude into the North Sea which disappeared before cleanup crews could reach the site. After two tankers collided in San Francisco Bay in 1971, Bunker C fuel oil was rapidly incorporated into near-bottom waters, to be transported independently from the surface slick. Following the wreck of the AMOCO CADIZ in 1978, emulsified oil was found to be homogeneous throughout the water column and contamination of bottom sediments had occurred. While monitoring the Hastab 6 well blowout in 1980, off Saudi Arabia, divers reported seeing layers of oil suspended several metres below the surface.

All oils initially have a specific gravity of 0.7 to 1.0 g/mL. At this density, oil would not sink in seawater. However, weathering by evaporation and dissolution of light components, emulsion formation, absorption of oil into particulates, and baterial growth can greatly increase the density. For example, weathering of Kuwait crude and Iranian heavy crude, both with an initial density of 0.869 g/mL, created a residue having a density of 1.023 and 1.027 g/mL, respectively (Jordan and Payne, 1980). Figure 1 presents further data on the increase in the density of oil upon weathering.

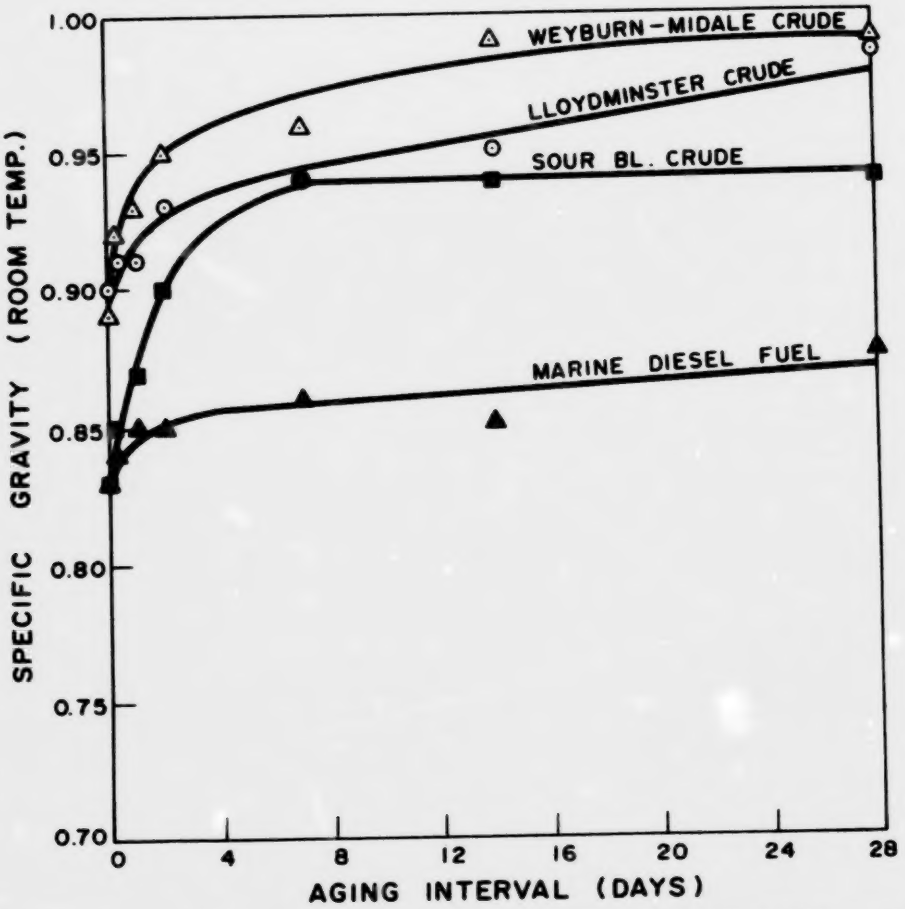

FIGURE 1 A GRAPH SHOWING THE INCREASE IN DENSITY OF VARIOUS OILS WITH AGING

Once the density of spilled oil increases to that of seawater, the oil will become entrained in the water column and its behaviour will be governed by physical oceanographic processes entirely different from those affecting a surface slick. This paper summarizes a study done for the Environmental Protection Service that discusses the processes affecting seawater density from the perspective of where spilled oil would be most likely to sink. The study includes contour maps of surface water density for all of Canada's coastlines, as well as typical vertical density profiles at stations in each area. In this paper, a written summary of the water density distribution for each of the major coastal areas is presented, together with some example data presentations.

## METHOD

Surface water density measurements, or temperature and salinity when necessary, were compiled from published and unpublished sources including technical reports, cruise data, and archived data held by the Marine Environmental Data Service. All of Canada's coastal waters, out to the 200-mile economic limit, were examined using computer-generated contour maps. The data were averaged seasonally. For Canada's Atlantic Coast, all four seasons were presented because of the strong influence of current systems. On the Pacific Coast, where there is less variability, only summer and winter conditions were presented. In the Arctic, only open-water conditions were dealt with because the behaviour of oil under ice was beyond the scope of the study. Representative seasonal vertical density profiles were used to characterize the water column structure. All of these data can be found in the report by Juszko et al. (1983).

## PHYSICAL CONSIDERATIONS

The dynamic behaviour of coastal waters can often be dictated by a change of as little as 0.1% in the density of the water. For example, a change of 0.1% could determine whether water is found at the surface or 100 metres deep. It is this level of precision which must be considered when studying the behaviour of oil in seawater. Any process which results in a change in the relative densities of either of the two fluids could significantly alter the oil's behaviour; however, only those processes affecting seawater density are examined here.

A change in temperature or salinity can alter the horizontal or vertical density distribution in coastal waters. An increase in temperature by an external heat input acts to reduce the density. This is normally associated with the seasonal solar heating cycle and can result in a density change on the order of 0.5% in surface water. This process is latitudinally dependent, with observed maximum temperatures in Canadian waters ranging from 5°C to 19°C.

Large variations in salinity are generally limited to nearshore waters; however, its effect on local density can be much larger than that of temperature (up to 3%). Ice melt from the pack ice edge or glaciers, and river run-off are the major sources of freshwater acting to reduce density.

The vertical density structure is characterized by the manner in which density changes with depth. Whenever two or more waters having different densities are present, they will align themselves with lighter water on top to become stable or stratified. The observed density profile is a balance between stratifying and mixing forces. Pycnoclines exist when a very rapid change of density with depth occurs. During the summer, in coastal waters, a shallow seasonal pycnocline at 20 to 75 metres develops as the surface layer warms from solar heating and mixing by winds is reduced. A second, deep pycnocline can exist in deep waters year-round between the surface mixed layer and a deep "isolated" layer. Sharp pycnoclines at shallow depths (less than 20 metres) are also present in areas of freshwater input.

Any process which vertically mixes the water column will disrupt this stratification, change the depth of a density surface, and thereby change the behaviour of oil of given density. Common areas of mixing are in shallows, over banks and ridges, and in estuaries. Vertical "boundaries" between two water bodies, called fronts, can be quite permanent in nature and are often associated with a given bathymetric or dynamic feature. Their presence is important because oil on either side of a front may behave differently. Known fronts exist at the edge of the Fraser River and Mackenzie River plumes, at shelf/slope breaks, in the Bay of Fundy separating mixed and stratified waters, in regions of ice melt, and in estuaries. Because surface density changes rapidly in these regions, and because fronts are often associated with shears in the flow, convergences or divergences, the exact location of an oil spill is important.

## SUMMARY OF RESULTS

Most of Canada's open coastal waters have surface densities in the seasonal range of 1.022 to 1.027 g/mL. Any oil of density greater than 1.027 will sink everywhere, at all times, and generally pass through the water column to the bottom. Surface water densities decrease to 1.000 in areas of freshwater influence, but these areas are very limited in their extent.

### Arctic Coast

Here, ice melt in semi-enclosed areas creates very shallow, often less than 5 metres thick, layers of brackish water. Densities as low as 1.005 g/mL can be encountered over a general background level of 1.025 g/mL. Very strong pycnoclines exist as well as strong horizontal density gradients. The entire region behaves like an estuarine system and flow may be decoupled between the two layers. As a result of a minimal increase in oil density through weathering, it may sink through the surface layer to rest on the pycnocline, with further motion independent of the surface.

Hudson Bay also behaves as a semi-enclosed estuary as a result of the many small rivers emptying into it. The counterclockwise flow around the bay creates a decrease in surface density from west to east. Surface water densities are reduced to 15-20 $\sigma_t$ over large areas. Figure 2 shows a computer-generated contour map of surface water density in Hudson Bay.

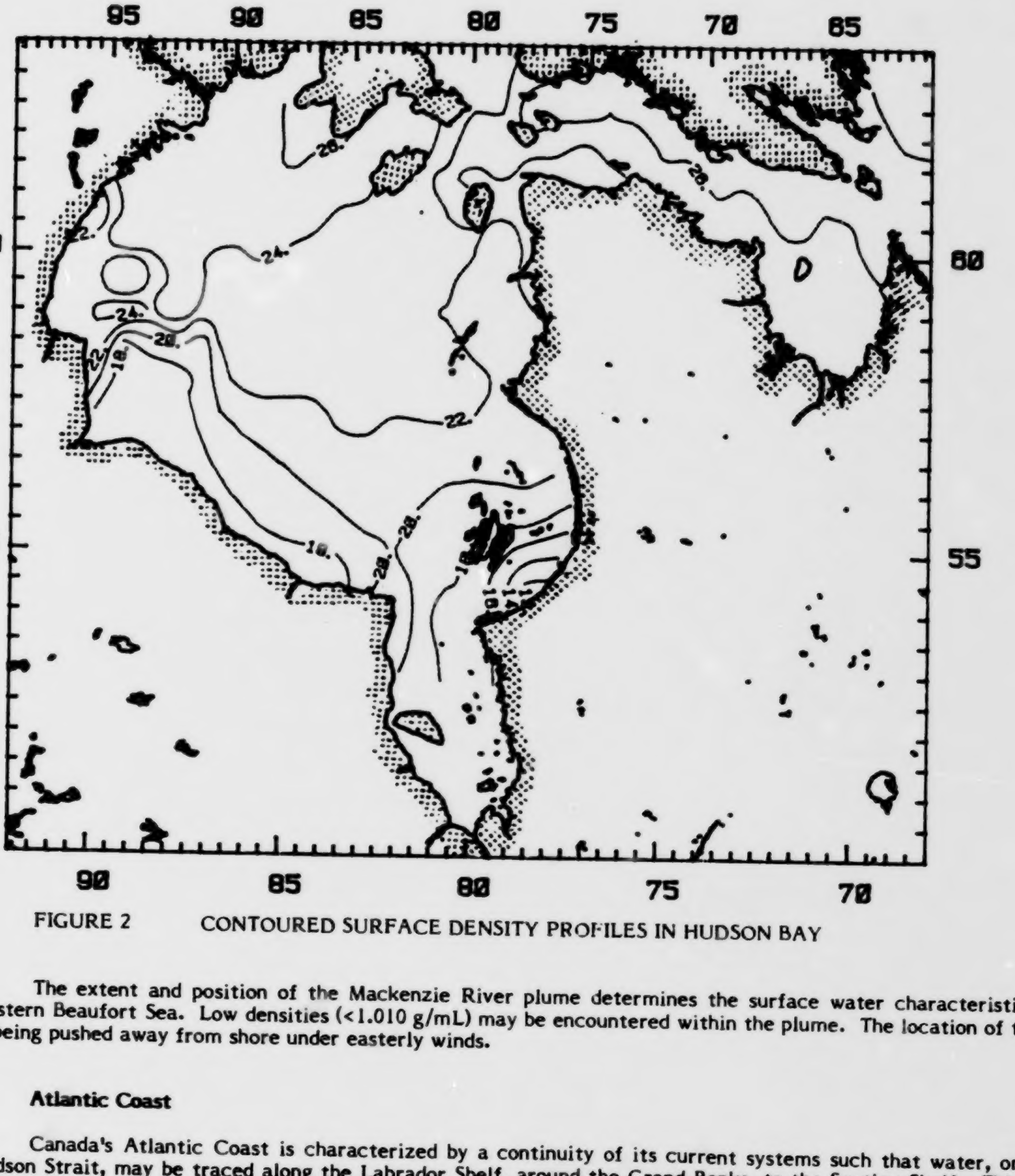

FIGURE 2 CONTOURED SURFACE DENSITY PROFILES IN HUDSON BAY

The extent and position of the Mackenzie River plume determines the surface water characteristics in the Southeastern Beaufort Sea. Low densities (<1.010 g/mL) may be encountered within the plume. The location of the plume varies, being pushed away from shore under easterly winds.

### Atlantic Coast

Canada's Atlantic Coast is characterized by a continuity of its current systems such that water, originating near Hudson Strait, may be traced along the Labrador Shelf, around the Grand Banks, to the Scotian Shelf. This coast is thermally and wind dominated. The seasonal solar heating pattern dictates the general density changes observed between 1.022-1.027 g/mL. The winds dictate the circulation patterns and the vertical structure encountered. Figure 3 shows typical vertical profiles on the Scotian shelf. There is usually a seasonal pycnocline at 20 to 75 metres.

Exceptions to this general picture exist. In the upper reaches of the St. Lawrence estuary and near the mouths of large rivers such as the Churchill River, surface densities can drop below 1.020 g/mL due to the influence of freshwater. In the Gulf of St. Lawrence, a shift of influence from salinity back to temperature occurs. In the upper reaches of the Bay of Fundy and on top of Georges Bank, shallow depths and strong tidal mixing result in a homogeneous water column throughout the year. The Gulf of Maine and Bay of Fundy are characterized by numerous shallow sea fronts between highly stratified and mixed waters.

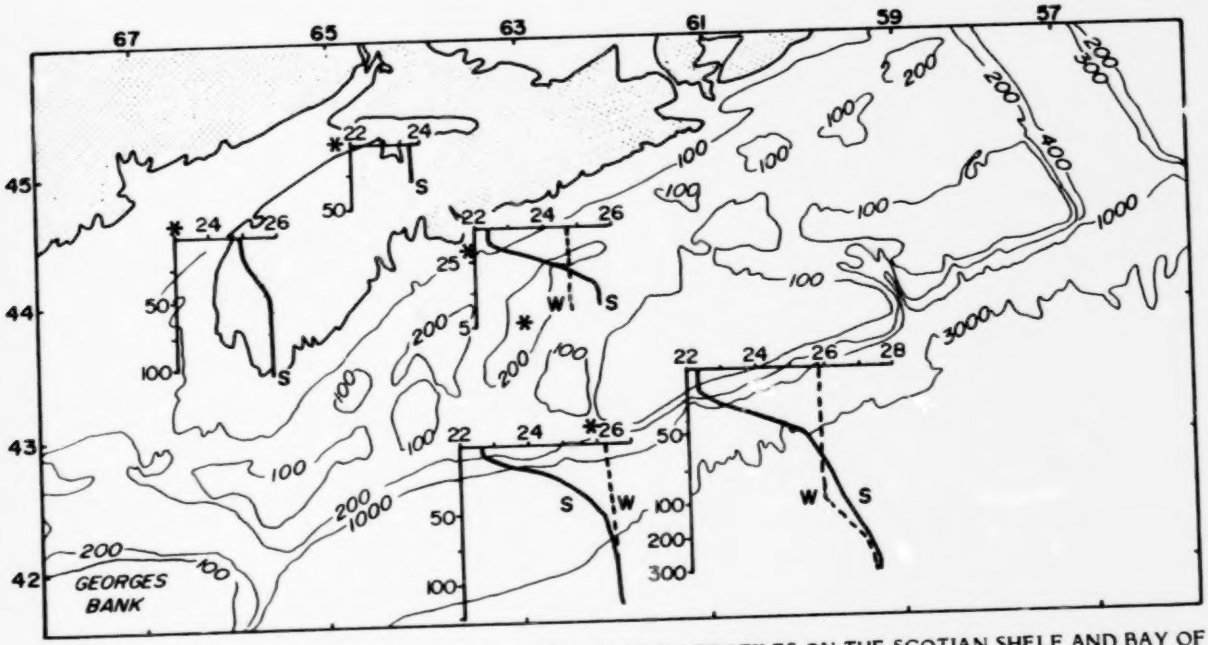

FIGURE 3 REPRESENTATIVE VERTICAL DENSITY PROFILES ON THE SCOTIAN SHELF AND BAY OF FUNDY (s = summer; w = winter)

**Pacific Coast**

Waters along Canada's Pacific Coast fall into two regimes: a) estuary or fjord dominated nearshore waters, and b) open-ocean conditions. High rainfall and river runoff, such as that of the Fraser and Skeena Rivers, into semi-enclosed areas create extensive regions of brackish surface water. This is especially true in the Strait of Georgia when surface densities can drop as low as 1.005 g/mL (see Figure 4). The circulation pattern is estuarine, such that oil in the surface and deep layer may move in opposite directions. In the "open ocean" regime, surface densities are thermally controlled.

## CONCLUSIONS

Large surface water density changes are associated with freshwater input. At high latitudes, ice melt provides the necessary freshwater; at mid-latitudes, river runoff is more important. However, these areas of pronounced freshwater influence are spatially very limited. For most of Canada's coastal regions, temperature plays the major role in determining density changes.

The behaviour of oil once it sinks will be determined by the vertical density structure. Very dense oil (>27 $\sigma_t$) would sink to the bottom in most coastal waters. Oil of density 20 to 27 $\sigma_t$ may become neutrally buoyant at an intermediate depth in the summer on a seasonal pycnocline (created by solar warming of surface waters). More dramatically, freshwater input often creates very strong pycnoclines at depths up to 20 m. Less dense oil (0 to 20 $\sigma_t$) would sink here but would become "trapped" at the pycnocline. Oil, once it has sunk to an intermediate depth of neutral buoyancy, will move with the water body, often in a manner quite contrary to any associated surface slick.

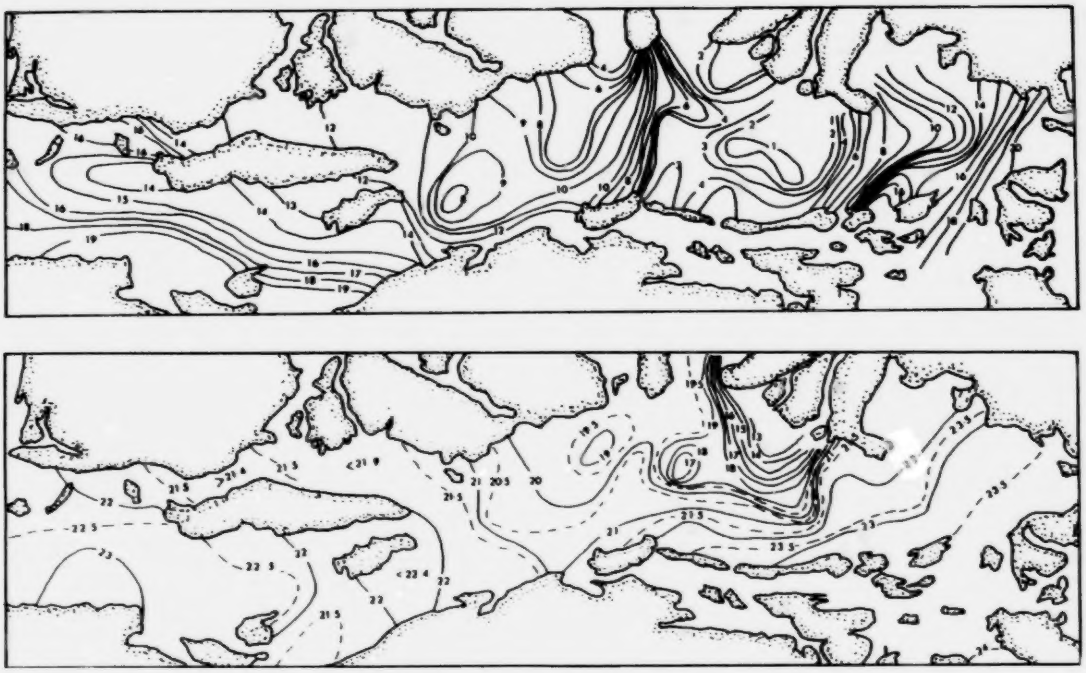

FIGURE 4 CONTOURED SURFACE DENSITIES IN THE STRAIT OF GEORGIA (upper = June; lower = February)

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# OIL BEHAVIOUR UNDER MULTI-YEAR ICE AT GRIPER BAY, N.W.T.

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## INTRODUCTION

As exploratory drilling in Canada's ice-infested waters continues, potentially serious oil pollution incidents have become of increasing concern. Several scenarios have been identified as probable mechanisms for the accidental discharge of oil and/or gas into an ice environment, including the rupture of oil and/or gas tankers and subsea pipelines, and subsea well blowouts. Consequently, several studies have been undertaken to determine the behaviour and fate of oil and gas released into an Arctic sea ice environment and to develop methods for Arctic oil spill cleanup.

The most extensive series of field tests to date were done at Balaena Bay, N.W.T. (NORCOR, 1975), in which approximately 60 m$^3$ of crude oil were discharged under a static, first-year ice cover. Subsequent field tests have examined the interaction of oil and gas mixtures with static, first-year ice (Buist et al., 1981). Recently, field tests have been undertaken at Cape Hatt, N.W.T., to determine the behaviour and fate of oil released on Arctic shorelines.

The interaction of oil released under multi-year ice is also of concern and has been the subject of an ongoing field program carried out by Environment Canada. Initial field studies near Resolute Bay, N.W.T. (Milne et al., 1977), attempted to estimate the porosity of multi-year ice in summertime conditions and to thereby infer the behaviour of an oil lens under multi-year ice.

In the following year, a field program consisting of a crude oil discharge under a static multi-year ice cover in Griper Bay, N.W.T., was undertaken (see Figure 1 for a location plan). A total of 1.84 m$^3$ (405 gallons) of Norman Wells crude oil was discharged under the ice on June 1, 1978, at three different sites (i.e., 0.61 m$^3$ at each site). The ice thickness varied from 2.5 to 2.9 m and was at least second year in age.

This paper reviews the behaviour and fate of the oil released at the site to date and presents the results of a site investigation made during September, 1982, to determine the quantity of oil still remaining on site.

## SYNOPSIS OF OIL BEHAVIOUR: DATA FROM EXPERIMENTAL SPILL SITE

After the initial discharges, the test area was overflown on June 13, 1978. There was no evidence of oil on the surface at that time. A subsequent overflight occurred on July 1, 1978. At that time, there was no evidence of oil at sites 1 and 2; however, a large crack had penetrated site 3 and oil was observed on adjacent melt pools.

Later on in the summer, on August 21, the spill sites were again overflown. Oil appeared to have surfaced but had not spread at sites 1 and 2, while considerable oil was visible on the surface in the vicinity of site 3. Site visits were then made in October, 1978 and in March, 1979. These missions failed to locate the oil spill sites and consequently were not able to provide information on the behaviour and fate of the oil released.

The Griper Bay experimental oil spill site was then occupied by Arctec Canada Limited and Environment Canada representatives during September, 1979 (Comfort and Purves, 1980). The spill sites were located using an airphoto taken on August 21, 1978, which showed oil on the ice surface. This was confirmed by drilling and coring, suggesting that the site locations measured by the discharge crew were incorrect.

Sites 1 and 2 were cored, and a small amount of oil was found at depths of up to 1.2 m. At site 3, no oil was found in the ice; however, some heavily weathered oil was present on the surface of a recently frozen crack. The quantity of oil still remaining in the ice sheet ranged from 0 to approximately 10% of the total volume of oil originally discharged. Twelve samples were selected for gas chromatographic analysis to estimate the extent of weathering of the oil remaining on the ice surface and within the ice sheet. Table 1 provides a brief synopsis of the study results.

## RESULTS OF SEPTEMBER, 1982, INVESTIGATION

The Griper Bay oil spill site was occupied over the period September 2 - 5, 1982, by a field crew consisting of three Arctec Canada Limited personnel and one Environment Canada representative. This section describes their observations.

The oil spill tests sites were first overflown on September 2, 1982. No evidence of oil could be seen from the air. Approximately 5 cm of fresh snow covered the site. Summer melt pools had refrozen with approximately 10 cm of ice and were surrounded by hummocks. The parcol left on site by the field crew of 1978 was in very poor condition. Differential melt had resulted in the centre of the parcol floor rising approximately 3 m above the surrounding terrain. It

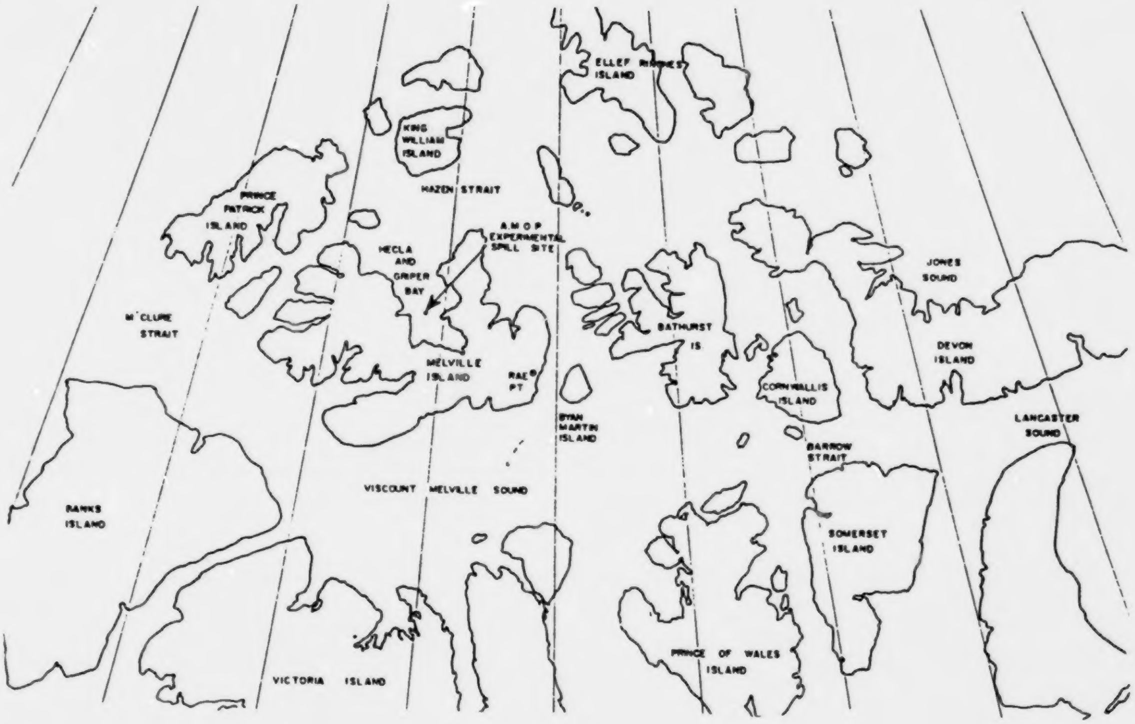
ELLEF RINGNES ISLAND
KING WILLIAM ISLAND
HAZEN STRAIT
PRINCE PATRICK ISLAND
A.M.O.P EXPERIMENTAL SPILL SITE
HECLA AND GRIPER BAY
M'CLURE STRAIT
MELVILLE ISLAND
RAE PT
BYAN MARTIN ISLAND
BATHURST IS.
JONES SOUND
DEVON ISLAND
CORNWALLIS ISLAND
LANCASTER SOUND
BARROW STRAIT
BANKS ISLAND
VISCOUNT MELVILLE SOUND
SOMERSET ISLAND
PRINCE OF WALES ISLAND
VICTORIA ISLAND

FIGURE 1 LOCATION OF SPILL SITE

TABLE 1 SUMMARY OF SEPTEMBER, 1979, SITE INVESTIGATION

| Site No. | 1 | 2 | 3 |
|---|---|---|---|
| Oil Volume in Ice: | | | |
| Amount of oil remaining in ice relative to total volume discharged at site | 1% | 10% | - |
| Estimated Mass Percent Evaporation | Surface Sample | Oil-in-Ice Sample | |
| Oil Weathering: | | | |
| Minimum | 37% | 12% | |
| Maximum | 43% | 20% | |
| Mean | 42% | 17% | |

is likely that no ice movement at the site had taken place since September, 1979, as the spill site location baseline (established during the 1979 site visit) remained unchanged. Figure 2 shows the site as found on September 2, 1982.

FIGURE 2 SITE CONDITION UPON ARRIVAL SEPT. 2/82

All sites appeared to have been covered by melt pools during the recently ended summer season. No cracks or pressure ridges were present in the area. The three spill sites were located using the site map prepared during the 1979 site visit. Each spill site was drilled extensively, cored, and photographed.

**Site 1**

Figure 3 shows surface conditions at sites 1 and 2. All holes drilled at site 1 showed no traces of oil; clean shavings were found throughout the 1.45 m ice thickness. Cores taken at site 1 also showed no traces of oil (see Figure 4).

FIGURE 3 SURFACE CONDITIONS AT SITES NO. 1 AND NO. 2

**Site 2**

Site 2 was also found to be devoid of oil. Figure 5 shows a core taken at Site 2. The ice thickness was measured to be 1.8 m.

**Site 3**

No oil or residue were found at site 3 either in auger holes or cores. Figure 6 shows a core taken at site 3.

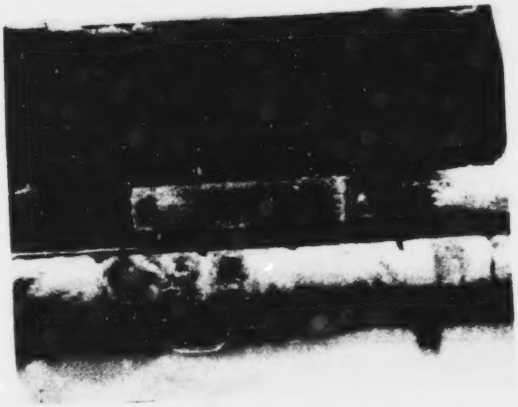

FIGURE 4 TYPICAL CORE AT SITE NO. 1

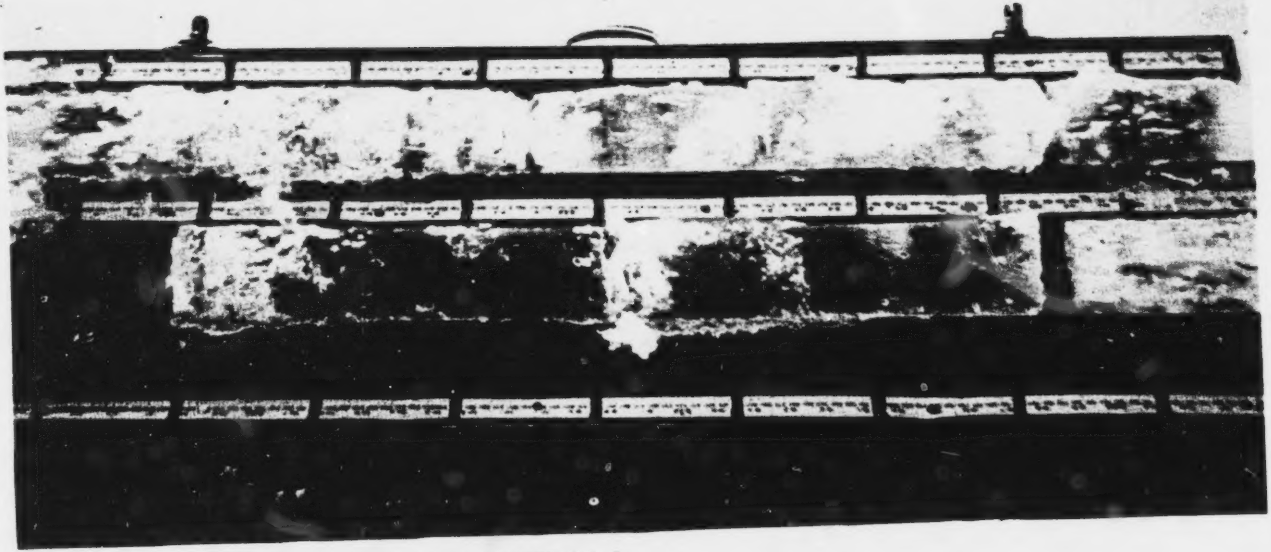

FIGURE 5 CORE TAKEN AT SITE NO. 2

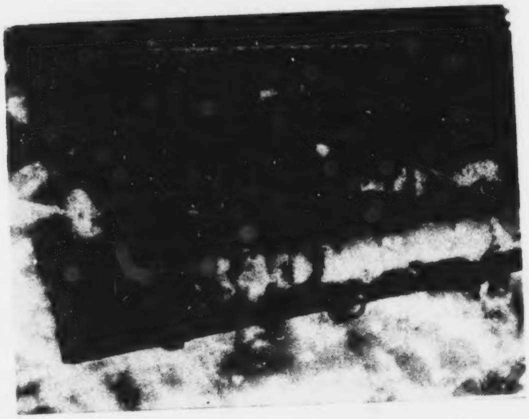

FIGURE 6 CORE TAKEN AT SITE NO. 3

## LONG-TERM OIL BEHAVIOUR

The persistence of oil released in an ice environment is an important parameter affecting the environmental impact of an oil spill and was viewed as one of the major overall objectives of the field program.

The Griper Bay spill site was surveyed in detail in 1979 and 1982 and has provided some understanding of the long-term behaviour and fate of oil released in a multi-year ice environment. Table 2 summarizes the oil-in-ice concentration data collected during the field program.

TABLE 2 OIL-IN-ICE CONCENTRATION DATA SUMMARY

| Time | Area of Oiled Ice (m$^2$) | Mean Ice Thickness (m) | Volume of Oil in Ice (m$^3$) | Mean Oil-in-Ice Concentration (%) |
|---|---|---|---|---|
| Spill Site 1 | | | | |
| June, 1978 (i.e., Discharged) | 6.1[a] | 2.7[b] | 0.61 | 3.7 |
| Sept., 1979 | 26.3 | 1.0 | 0.0038 | 0.007 |
| Sept., 1982 | 0[c] | 0[c] | 0[c] | 0[c] |
| Spill Site 2 | | | | |
| June, 1978 (i.e., Discharged) | 3.1[a] | 2.7[b] | 0.61 | 7.3 |
| Sept., 1979 | 11.6 | 2.2 | 0.065 | 0.25 |
| Sept., 1982 | 0[c] | 0[c] | 0[c] | 0[c] |

Area of oil pool underneath ice immediately after discharge.

[b] Mean ice thickness at time of discharge.

[c] Below measurable limits.

As discussed in detail in a previous paper (Comfort and Purves, 1980), the 1979 study found that the behaviour of the oil at the three individual sites was somewhat dissimilar although general similarities and conclusions were apparent. The September, 1979, field trip showed small amounts of oil still remaining on the ice at sites 1 and 2 (i.e., approx. 1% and 10% of the volume initially discharged, respectively), while no oil was found in the ice at site 3, probably reflecting the effect of penetration by a crack in 1978.

This field survey has extended the 1979 data by providing further information on the rate at which the quantity of oil remaining in a multi-year ice environment, due to a small spill, will decay with the passage of time through the natural processes of dispersion and evaporation.

The available data can be bounded by an inverse exponential equation of the form:

$$V = me^{-bt}$$

where $V$ = mean oil-in-ice concentration (in percent)

$t$ = number of melt seasons after the oil discharge occurred

Constants for the above equation have been evaluated on the basis of the available data to determine upper and lower bound solutions using the following assumptions:

(a) Mean oil-in-ice concentrations of 0.00001% will not be detected by a visual inspection; consequently, this value has been used as the endpoint value for the available data.

(b) The lower bound solution is based upon an observed oil-in-ice concentration of 0.007% (i.e., site 1 data) after two melt seasons had elapsed, and an assumed oil-in-ice concentration of 0.0001% after three melt seasons.

(c) The upper bound solution is based upon an observed oil-in-ice concentration of 0.25% (i.e., site 2 data) after two melt seasons had elapsed, and an assumed oil-in-ice concentration of 0.0001% after five melt seasons.

The following constants were obtained:

| SOLUTION | m | b | $r^2$ |
|---|---|---|---|
| Lower Bound | 4.4 | -3.5 | 0.994 |
| Upper Bound | 11.3 | 2.3 | 0.988 |

Figure 7 graphically shows the decay of the oil-in-ice concentration as predicted by the above lower and upper bound descriptors.

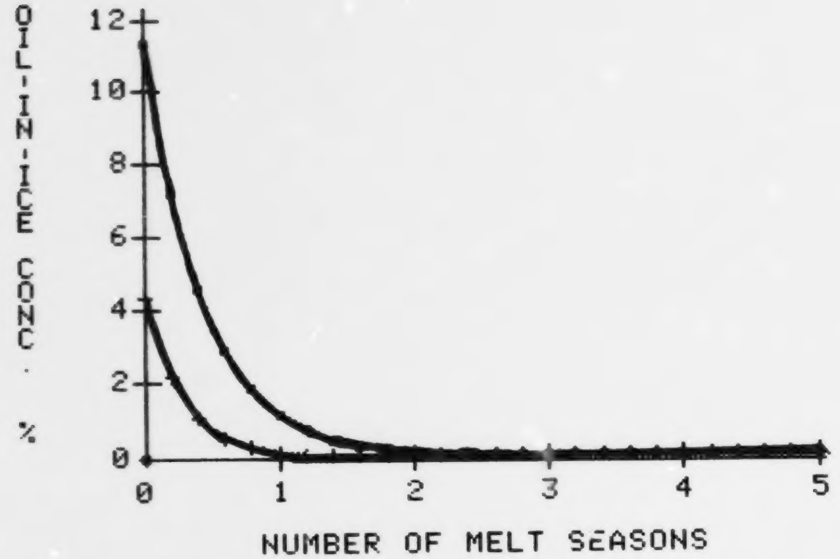

FIGURE 7 OIL IN MULTI-YEAR ICE

From the results of this study, it is apparent that a small crude oil spill under multi-year ice will surface quickly and be acted upon by the forces of dispersion and evaporation so as to reduce the concentration of oil in the environment to be visually undetectable, within at the most five melt seasons.

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# A TWO-DIMENSIONAL NUMERICAL MODEL FOR PREDICTING THE CONCENTRATIONS OF OIL UNDER A SLICK

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## INTRODUCTION

Once oil is released in the marine environment, data on the vertical and horizontal distribution of the oil in the water column is required in order to assess the impact of the oil on the biota. Unfortunately, these data are difficult to come by as the vertical and horizontal distribution of oil in the water column is dependent on the composition of the oil spilled and the environmental conditions under which the spill occurs. That is, the vertical and horizontal distribution of spilled oil is site- and incident-specific in the extreme! However, the availability to OCSEAP of a satisfactory model for depicting the entry rate of dissolved and dispersed oil into the water column from surface slicks of various compositions and under various environmental conditions (Payne et al., in press) made it very attractive to seek a method of predicting the resulting water column concentrations (Figure 1).

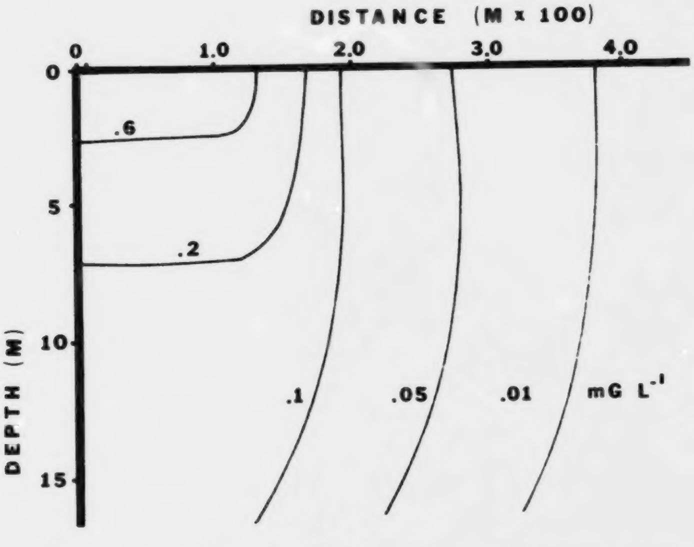

FIGURE 1 THEORETICAL CONCENTRATION CURVES OF DISSOLVED AND DISPERSED OIL IN THE WATER COLUMN UNDER AND AROUND A SURFACE SLICK OF PRUDHOE BAY CRUDE OIL AT 0.5 DAYS. The dilution curves are symmetrically distributed around a 200 m wide slick. This solution assumes a persistent 5 m/s wind.

Water column concentrations under and around a long, narrow slick can be modeled with a two-dimensional diffusion equation by assuming the only relevant transport processes are vertical and horizontal diffusion. Longitudinal diffusion may be ignored on the grounds that in the direction parallel to the elongation of the slick, gradients are negligible. Advection is omitted for the sake of computational simplicity. These assumptions define a highly conservative model. In the real world, tides and variation in winds alone are enough to cause advection which will diminish the concentration below the values found from this simplified two-dimensional diffusion model.

This model assumes the continuous motion of a slick emanating from a constant source. The slick is assumed to spread and disperse into the water column. At the point of observation downwind of the origin, the width and dispersion rates are assumed to be constant. The model looks at a plane normal to the axis of the slick, with a coordinate system in the plane whose origin is at the centerline of the slick. Symmetry is assumed, so only one half of the solution needs to be computed. By neglecting advection and decay terms, the transport equation is reduced to:

$$\frac{\partial C}{\partial t} \doteq K_z \frac{\partial^2 Z}{\partial Z^2} + K_y \frac{\partial^2 Y}{\partial Y^2} \qquad (1)$$

The vertical and horizontal diffusion coefficients are chosen on the basis of area of interest and local conditions. Cline et al. (1982) calculated a vertical diffusivity of 185 $cm^2/s$ from salinity data collected in the southeastern Bering Sea. The water column in the area examined was well-mixed. Alternatively, a value of 25 $cm^2/s$ has been calculated by Liu and Leendertse (1982) for typical partially stratified water such as in the lagoons of the Beaufort Sea coast. Computed values for horizontal diffusivities range from $5.5 \times 10^3$ in the New York Bight to $2.8 \times 10^6$ cm/s in the Bering Sea shelf (Okubo, 1971; Coachman and Charnell, 1979). Wilson et al. (1981), using drogues, measured horizontal diffusion in Harrison Bay (Alaskan Beaufort). They reported values of 780 to 8,400 $cm^2/s$ for diffusion in the transverse axis of the ellipses studied. In the solution illustrated herein, we used $K_y = 3{,}500$ $cm^2/s$ and $K_z = 25$ $cm^2/s$ in order for the depicted dilution curves to have relevance to oil spills in the shallow, partly stratified water of the southeastern Bering Sea or Harrison Bay.

Equation 1 was solved by using a finite difference equation such as described by Wang and Anderson (1982). The difference equation is:

$$C^{N+1}_{ji} = C^N_{ji} + \Delta t \cdot K_z \, (C^N_{j,i+1} + C^N_{j,i-1} - 2C^N_{j,i})/\Delta Z^2$$

$$+ \Delta t \cdot K_y \, (C^N_{j+1,i} + C^N_{j-1,i} - 2C^N_{j,i})/\Delta Y^2 \quad (2)$$

The notation used in equation 2 indicates that the (N+1)th iteration is being considered. The concentration C is being found in a location defined by coordinates i and j. The time increment between iterations is $\Delta T$; $K_z$ and $K_y$ are the diffusion coefficients; and $\Delta Y$ and $\Delta Z$ are the spacings in the horizontal and vertical grids.

As the model as run, $C^N_{j,o}$ was incremented to account for the addition of dissolved and dispersed oil at the surface under the slick. The concentration gradient between the surface (i = 0) and the first grid below the surface (i = 1) was adjusted in each iteration in such a way that the flux of material $(C_o - C_1) \times K_z$ equaled the rate of material dispersion from the slick as defined by Payne et al. (in press).

The code to implement equations 1 and 2 was tested for consistency with an analytical solution by reducing the horizontal dispersion to zero and plotting the vertical distribution. Figure 2 shows one of the results for typical diffusion coefficients. Equation 2, though relatively simple to implement, does not conserve material balance. In effect, material is added as the solution progresses within each iteration. In order to preserve material balance, the excess was kept track of during the progress of the solution and an equivalent amount substracted from the increment added at the surface at each time step.

In conclusion, we used this model to examine the concentrations of hydrocarbons in the water column below and around an increasing slick such as that caused by a continuous spill. In this case, it was assumed that the wind was sufficient to move the slick past the point of interest but that there was no horizontal shearing in the water column. This slick is illustrated in Figure 3. The cross-section line is at a point 2 hours downstream from the spill site. The hydrocarbon concentrations in the water column at the point of observation are similar to those in Figure 1. Because advection and convection processes are ignored in this treatment, the result is a continuing increase in the hydrocarbon concentrations for as long as the release lasts (Figure 4). Once the release ends (or the wind shifts), the concentrations will diminish as further diffusion takes place.

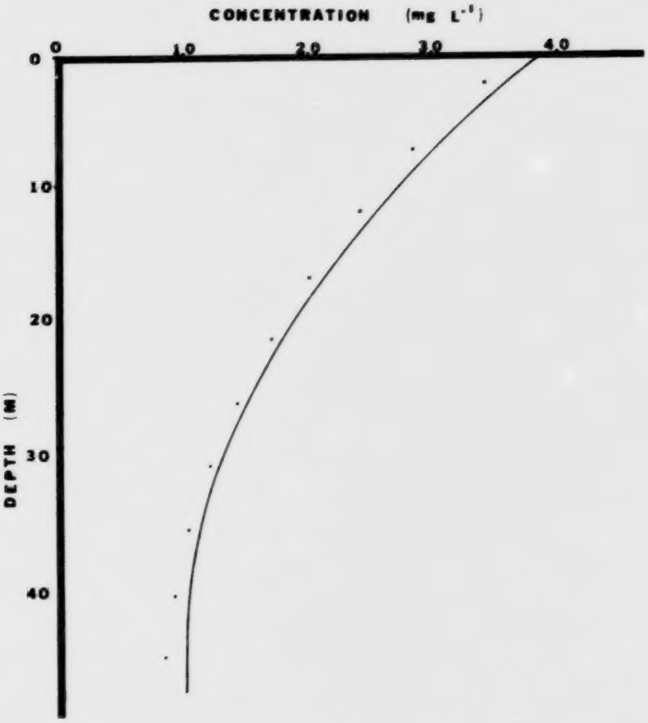

FIGURE 2 COMPARISON BETWEEN THE ANALYTICAL SOLUTION AND THE FINITE DIFFERENCE SOLUTION. The horizontal diffusion (Ky) was reduced to 0 in order to similate the analytical solution in one dimension. Material balance was maintained as described in the text.

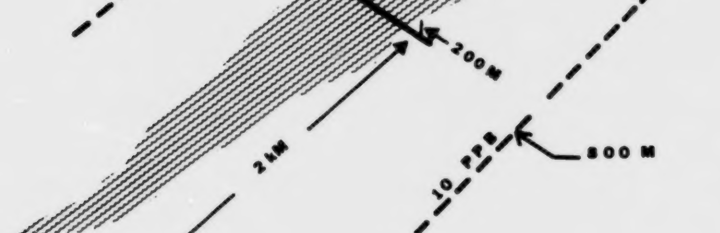

FIGURE 3 THEORETICAL OIL SPILL. The finite difference solution can be used to describe the time-dependent two-dimensional distribution of oil in the water column at the point indicated.

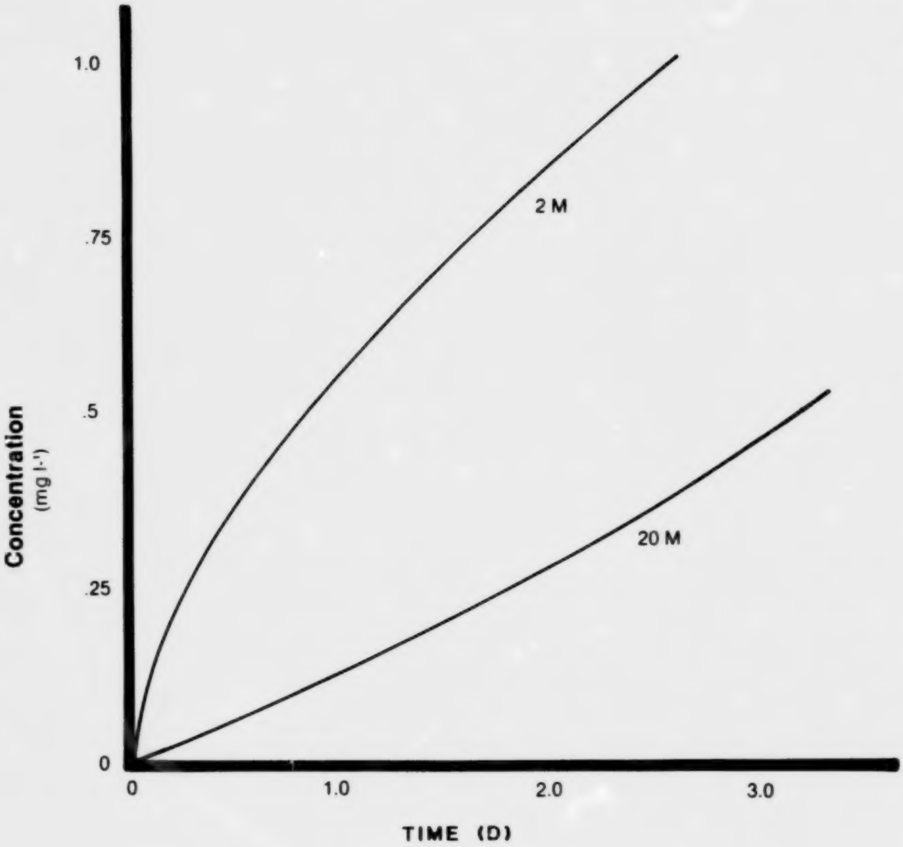

FIGURE 4 INCREASING CONCENTRATIONS OF OIL IN THE WATER COLUMN. This solution assumes a constant imput of hydrocarbons into a stationary water column such as would occur at the point of observation in Figure 1. Once the spill ends or the winds shifts, the concentration will diminish.

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# RECENT UNIVERSITY OF TORONTO STUDIES ON THE FATE AND EFFECTS OF OIL IN THE MARINE ENVIRONMENT

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## INTRODUCTION

This paper gives a brief review of some of the on-going projects at the University of Toronto on aspects of oil pollution. Not included here is work, described elsewhere in these proceedings, by P.G. Wells on the toxicology of oil, dispersed oil and dispersants being conducted at the Bedford Institute of Oceanography under Imperial Oil sponsorship; by M. Bobra on the toxicity of hydrocarbons and crude oils to *Daphnia magna* in freshwater systems sponsored by the Inland Waters Directorate of Environment Canada; and work described by D. Mackay, K. Hossain and A. Chau on dispersant effectiveness evaluation.

It should also be noted that there is continued interest and activity elsewhere at the University of Toronto in fundamental studies of oil toxicology in the groups headed by Dr. T.C. Hutchinson in Botany and by Dr. J. Berger in Zoology.

The work described here has been or will be published in more detailed reports; thus, only a brief review is presented. The topics include studies of evaporation, water-in-oil emulsion formation, standard test protocols and models for crude oils, response to spills of opportunity, and a general review of the physical behaviour of oil in the Arctic marine environment.

## EVAPORATION OF OIL

Our group has been studying evaporation processes for more than 10 years. The importance of the process is obvious; it affects the mass of the oil as well as its density, viscosity and combustibility. Several approaches can be taken, the first most commonly being a "pseudo-component" approach used by Yang and Wang (1977), and Reinjhart et al. (1982); most recently, a very comprehensive and detailed model was presented by Payne et al. (1983). We have chosen to explore the "analytical" approach in which the changing oil vapour pressure is characterized by an analytical expression. The approach is briefly described below; a more detailed account is in preparation (Stiver and Mackay, 1983).

The evaporation rate is described by the following expression:

$$N = K_m A P_E / RT \tag{1}$$

where $N$ is the molar flux, mol/s,

$K_m$ is a mass transfer coefficient, m/s

$A$ is the oil spill area, $m^2$

$P_E$ is the oil's vapor pressure, Pa

$R$ is the gas law constant, 8.314 $m^3$ Pa/gmol K

$T$ is the oil's environmental temperature

We can also write:

$$N = (V_o/v)dF_v/dt \tag{2}$$

where $V_o$ is the initial volume of oil spilled, $m^3$

$v$ is the molar volume of the oil, $m^3$/mol

$F_v$ is the volume fraction evaporated

$t$ is the time, s

Therefore, equation (1) becomes:

$$dF_v/dt = \frac{K_m A}{V_o} \cdot \frac{P_E v}{RT} \qquad (3)$$

Here we have defined equation (3) in terms of volume fraction evaporated. Mass fraction is also commonly used. The difference between these two can be significant.

Integration gives:

$$F_v = \int_0^t (P_E v/RT)\,(K_m A/V_o)dt$$

If the oil is a single substance, $P_E$ is constant and integration gives the extent of evaporation $F_v$ as a function of two very convenient dimensionless groups:

$$F_v = (P_E v/RT)\,(K_m At/V_o)$$

$$= H\theta$$

The group $(P_E v/RT)$ is actually a dimensionless air-oil partition coefficient or Henry's Law constant, and is a property of the oil at a given temperature. The group $\theta$ is termed an evaporative exposure and depends on wind speed (through $K_m$), time, and area and volume (i.e., thickness). Evaporation is complete when $\theta$ reaches a value of $(1/H)$.

For an oil mixture, $P_E$ varies as a function of $F_v$; integration is thus more complex. The problem is to devise experimental methods for obtaining data which can be used to relate $F_v$ to time or to $\theta$.

It is important to note that the fraction evaporated of a particular oil is not just a function of time. The statement that the oil is "one day weathered" is meaningless. It tells nothing about the actual exposure, $\theta$, of the oil. Clearly, a slick of oil 0.1 mm thick exposed for 1 day under wind speeds of 50 km/h will be much more weathered than a slick 1 cm thick exposed to wind speed of 20 km/h. As a rule of thumb for a typical oil spill, the exposure, $\theta$, equivalent to 1 day is about 900,000 ($K_m = 0.01$ m/s), $V_o/A = 1$ mm, $t = 86{,}400$ s). Correlations are available in the literature for predicting mass transfer coefficients ($K_m$) as a function of wind speed.

The techniques that have been developed for investigating evaporation rates at the University of Toronto are tray evaporation, gas stripping, and distillation. The purpose of these evaporation techniques is twofold: to be able to produce samples of weathered oil for further experimental studies (i.e., density, viscosity or dispersability determinations); and to enable predictions to be made of evaporation rates for use in modeling.

Gas stripping (or air bubbling) is a technique in which air or nitrogen is slowly bubbled through the oil. The flowrate is slow enough that the exiting air is essentially saturated by the hydrocarbons. It can be shown that for this case the evaporative exposure, $\theta$, is $Gt/V_o$, where G is the gas flowrate ($m^3/s$) and t and $V_o$ are as defined before. This method is accurate, but its major drawback is that it is exceedingly slow. To obtain an exposure, $\theta$, of 100,000 requires 100,000 L of air for every 1 L of oil. At reasonable air flowrates, this takes upwards of 15 to 20 days. Still, this exposure is only equivalent to 2 or 3 hours under "normal" environmental conditions. The fact that most of the evaporation takes place during this early period makes this technique feasible for sample production.

The tray evaporation technique more closely resembles actual environmental situations. However, one must be careful in applying mass transfer coefficient correlations obtained in open areas. For wind tunnel experimentation, the coefficient should be determined specifically for that physical situation. The experiments conducted at the University of Toronto use wind speeds of between 5 and 12 m/s, with an oil slick thickness ($V_o/A$) of approximately 3 mm. This allows us to obtain exposures of about 400,000 per day. This technique is thus suitable for use in determining realistic extents of evaporation for crude oils. It is also useful for producing samples of weathered oil that could not be obtained by the gas stripping technique.

In actual environmental oil spills, a large area of oil termed "sheen" is often observed surrounding the bulk of the slick. This sheen is very thin, possibly having a thickness ($V_o/A$) of 0.01 mm, plus or minus a factor of 4. Thus, the exposure of this oil in a single day may reach $10^8$ under normal wind conditions. Evaporation will thus be exceedingly rapid and "complete" within hours. Obviously, exposures of even $10^9$ could easily be obtained. The normal tray evaporation technique can realistically only reach exposures of $10^7$. Experiments using extremely thin films of oil have been conducted at the University in an attempt to reach these values. However, the accuracy of the exposure measurement under these conditions is questionable. The thin-film technique is useful for determining a "maximum extent of evaporation" for a particular oil, but cannot be used to produce samples of oil at these large exposures.

The time involved in determining the evaporation characteristics of crude oil by the above two techniques is thus formidable. It is desirable, as an alternative, to be able to predict the evaporation curve from a distillation curve. The distillation curve of an oil contains the necessary vapor pressure information but it must be compensated for the temperature difference. A distillation technique has been set up to produce reproducible distillation curves. The advantage of this technique is that it is fast and can produce large samples of approximately the "correct" oil composition. It is regarded as less accurate than the tray evaporation method. The ASTM D-83 method could not be used directly; the procedure was therefore modified.

Using Trouton's Rule and the Clapeyron-Clausius Equation, it is possible to relate $P_E$ (and thus H) to the boiling temperature $T_B$ (K). We have studied five crude oils and have obtained the relation:

$$H = \exp(6.3 - 0.035\, T_B)$$

Since $T_B$ can be related to $F_V$ by the distillation curve, for example most simply by a linear expression,

$$T_B = A + BF_V$$

we can relate H to $F_V$ and integrate the evaporation equation to obtain $F_V$ as a function of $\theta$, namely:

$$F_V = \ln\{0.035\, B \exp(6.3 - 0.035A)\theta + 1\}\ (0.035B)$$

or

$$\Delta F_V = \exp\{6.3 - 0.035\,(A+BF_V)\}\ \Delta\theta$$

We can use these equations to correlate tray evaporation data and estimate evaporation rates under marine conditions.

In summary, we are now able to measure oil evaporation rates over the entire spectrum of feasible environmental exposures and temperatures. Samples can be easily produced for further experimental work for exposures up to $10^7$ (equivalent to approximately 12 days under "normal" environmental conditions). Modeling can be done fairly accurately from distillation curves (liquid boiling temperature) for exposures up to $10^7$. Beyond $10^7$, the prediction becomes somewhat suspect, but this is of little environmental importance. We therefore now have sound, quantitative expressions for evaporation rates as a function of environmental conditions, especially temperature, the critically different variable under Arctic marine conditions.

## WATER-IN-OIL EMULSIONS

We reported, in the 1982 AMOP Technical Seminar, studies on water-in-oil emulsions and particularly a standard emulsification test; a hypothesis proposed that emulsion stability was influenced by a combination of wax and asphaltene contents, as well as by temperature. Our work in this area has continued and we have updated some of our procedures and hypotheses.

The standard test which we proposed involved the use of a rotating bottle containing water, oil and air. Further tests have indicated that better results are obtained by increasing the water-to-oil ratio to approximately 10 in order to form an emulsion with a water content of 85%; an abundant excess of water still remains. The use of lower ratios of water to oil may tend to "starve" the system of water. A report describing this new system is being compiled.

Considerable effort has been devoted to standardizing the analytical methods for determining wax and asphaltene contents. There is now a standard asphaltene content determination; however, the accurate and precise determination of waxes still presents some difficulties. We also see the need to establish, or select, methods for determining paraffin, aromatic, and resin contents. Much of the early literature (including ours) reporting asphaltene content measurements is suspect because of variations in method.

An interesting development has been a review of Russian literature on emulsions (Novak and Mackay, 1983). This literature has been entirely ignored in the West partly for language reasons, but partly because the emphasis in the USSR is on de-emulsification during production of crude oils and not on environmental emulsification. A considerable amount of investigative work has been reported which throws new light on the crude oil emulsification process.

Briefly, the USSR work indicates that emulsions are stabilized by colloidal particles which gather at the oil-water interface and may combine to form a near-solid barrier which resists deformation and thus water-water coalescence. These particles may be mineral (clay), coal-like, wax crystals, aggregates of tars and asphaltenes, or mixtures of these various types. Asphaltene aggregates or "particles" are probably the most important. The formation of these particles is controlled by the asphaltene content and by the paraffin/aromatic ratio of the oil. More paraffinic oils (which are often more waxy) tend to form stabilizing "particles" more readily because the aromatics tend to disrupt or dissolve the "particles". This is consistent with previous claims that waxes stabilize emulsions in that (a) waxes may form stabilizing micro-crystals, and (b) high wax content may be an indication of high paraffin content or high paraffin/aromatic ratio. Some substances (termed deflocculants), which can be found almost exclusively in the silica gel resins fraction, retard coagulation of asphaltenes. These substances render the formation of the protective layer more difficult, in addition to the similar dissolving action effect of the aromatic content. A dimensionless stability criterion number, U, has been proposed, namely:

$$U = AC_P/(C_R C_A)$$

where A is the asphaltene content, mass %

$C_P$ is the paraffin content, mass %

$C_A$ is the aromatic content, mass %

$C_R$ is the silica gel resin content, mass %

When this number exceeds approximately 0.5, the oil tends to form stable emulsions. The terms "asphaltenes", "silica gel resins", "aromatics" and "paraffins" have only physical analytical operational definitions and lack a specific chemical identity. Before substituting them into the formula, the analytical results are corrected for the presence of some other chemical compounds in the respective fractions.

We are currently testing this and other hypotheses by preparing blends of different crude oils to achieve various contents of asphaltenes and other groups. Attempts to isolate asphaltenes and re-constitute "synthetic" oils are now believed to be unreliable because the asphaltenes change in composition when isolated. It should be noted that the effect of temperature is not included in this criterion, an obvious omission in the case of Arctic marine considerations. We are also attempting to devise novel methods of "probing" for the presence of the "particle barrier" by other methods such as electrical and optical techniques. Our aim is to devise an analytical protocol and a standardized test which can be used in combination to determine emulsion formation rate and stability. Ultimately, it is hoped that a rate expression can be devised which will be suitable for incorporation into oil spill models and which will be able to take account of the dependence of emulsion formation rate on oil properties, as well as the effects of temperature, sea state and weathering. We should then be able to quantify the emulsion formation tendency of a specific oil, fresh and as it weathers, at the desired temperature. This information will be invaluable for countermeasures planning and especially for deciding on the use of dispersants. The on-scene dispersant effectiveness test described elsewhere in these Proceedings will also be useful in this respect.

## STANDARD TEST PROTOCOLS AND MODELS FOR CRUDE OILS

It is obvious that different crude oils behave very differently at sea; their impacts may vary greatly depending on factors such as tendency to spread, evaporate, emulsify and disperse. There is a need to develop a standard set of determinations to which an oil can be subjected, particularly for countermeasures planning and environmental impact assessment purposes. In a project jointly funded by AMOP and the U.S. Coast Guard, we have discussed a possible set of determinations covering processes including spreading, evaporation, natural and chemical dispersion, emulsification, dissolution, and interactions with sediments and with ice. It is, we believe, important to make the determinations in a form that yields coefficients which can be inserted directly into algorithms in oil spill models which can then be used in a scenario or real-time mode.

In order to give this work maximum exposure, we elected to publish it in the Proceedings of the 1983 Oil Spill Conference (Mackay et al., 1983) rather than as an EPS report. Ultimately, it may be desirable for EPS to produce more specific guidelines for proponents of a given offshore development.

There are two possible sequels to this work. There may be a need for a set of standard biological tests to which an oil can be subjected, including toxicity evaluations and microbial degradability assessment. We also see a need for standardization of oil spill model methodologies when used in environmental impact assessments such that a proponent can follow a rigorous, impartial procedure when presenting scenario models. Considerable progress has been made in recent years, and the outputs of scenario models such as have been presented by Dome, Gulf and Esso (1982) in connection with the Beaufort Sea Proposal now yield information of a much higher quality than has been available hitherto. A problem of credibility remains, however, in that some critics are suspicious that only "favourable" scenario conditions have been selected by the proponent. We are doing some preliminary work in this area and in particular examining the role of "receptor mode" modelling (which means running the oil spill in reverse time), in which the aim is to determine which sources will cause an impact at a particular vulnerable location rather than which locations will be impacted by a particular source. This approach has been pioneered by Galt and Payton (1983).

Now that it is possible (and there is a requirement!) to make higher quality assessments of the impact of oil on the marine environment, there is a need to standardize laboratory and computational procedures which provide data to support these assessments. It would perhaps be valuable at this stage to compile a hypothetical, high quality specimen study integrating physical-chemical property measurements, their correlation to yield coefficients, their inclusion in an oil spill model, and the use of the model in a specified hypothetical situation. Since Governments require detailed, impartial, oil spill scenarios, perhaps they should give proponents a specimen to work towards, rather than merely demand the "state of the art".

## RESPONSE TO SPILLS OF OPPORTUNITY

A great deal has been learned about oil spill behaviour from careful scientific observations made at actual spill sites. In the event of a spill in Canadian waters, it is thus desirable that a well-planned and executed program be mounted to respond to such a "spill of opportunity". We have recently completed a 2-year program in this area.

The initial effort was to review the response literature on a world-wide basis, the review having been published as EPS Report EE 31. Two companion reports were produced simultaneously, one for the Atlantic Coast by Keizer, Hutcheson and Hurlbut (EE 30) and one for the Pacific Coast by Green, Humphrey and Fowler (EE 36).

In the more recent work, the following questions were addressed "what is the information which can best be obtained from spills of opportunity?" and "what are the priorities?" A review of oil slick behaviour processes was compiled and priorities assigned to information needs. The processes considered were the natural processes of spreading; drifting; evaporation; mousse formation; natural dispersion; dissolution; bio-uptake; horizontal and vertical diffusion in the water; volatilization from water; association with suspended bottom and shore sediments; sinking; biodegradation; photolysis/oxidation; and ice interactions. The following countermeasures were also considered: containment; collection and disposal; burning; absorption; and chemical treatment with dispersants, de-emulsifiers, gelling agents, and sinking agents.

A list of priorities was established, and general procedures were documented for making measurements, obtaining samples, and conducting analyses. It is hoped that there will be a final effort in synthesis which will include the preparation of detailed equipment inventories and locations. This is being done in collaboration with Dr. David Green and Dr. Paul Keizer.

## REVIEW OF THE FATE AND BEHAVIOUR OF OIL IN COLD CLIMATES

As AMOP matures, there is a need to review and consolidate progress, identify data gaps, and gather the relevant information in a unified form suitable for consumption by the scientific, lay and even political communities. Accordingly, a review has been started of the behaviour and fate of crude oil and dispersed crude oil in cold marine climates. Emphasis is on Canadian Arctic waters. Its primary purpose is to assemble and comment upon the available information, with a view to using the document as a basis for preparing subsequent reports and manuals which may be used by Environment Canada for purposes such as training of operational personnel, education of various groups ranging from the public at large (including especially those who live in the Canadian Arctic and may be directly affected by petroleum developments), to those involved in regulatory activities in various governments and departments, and to those undertaking supporting physical and biological scientific studies of this issue. It is envisaged that a text similar in format to "Basics of Oil Spill Cleanup" will ultimately be produced.

The focus of this report is on the physical and chemical behaviour and fate of oil, not on its effects on marine organisms. The only biological material are brief discussions of the role of biodegradation as a fate process and of oil sedimentation by association with organisms.

Because of the volume of information, a format has been adopted which has facilitated the preparation of the review and, it is hoped, makes it easier to read and use as a reference source. The broad topic has been divided into a number of subtopics. Each topic is treated separately by first an introduction and statement of scope and importance, then a review of the current understanding of the process and its implications. The subtopics are:

(a) Spill volumes (i.e., the statistics of tanker and blowout releases)

(b) Oil types and characteristics (especially physical properties)

(c) Oil release conditions (e.g., onto or under ice or water, or into air)

(d) Interactions with ice

(e) Spreading and drift

(f) Evaporation of hydrocarbon solutions from slicks and from water

(g) Dispersion (oil-in-water emulsification)

(h) Mousse formation (water-in-oil emulsification)

(i) Dissolution

(j) Chemical and biochemical conversion processes

(k) Interaction with sediment

The report will be complete by March 1984.

## CONCLUSIONS

This report, together with the other three reports in these Proceedings, gives a fairly comprehensive account of research efforts based at the University of Toronto. In recent years, this work has made use of approximately six persons full-time, at an annual cost of some $200,000. Most of this support has come from Imperial Oil, AMOP and BP(UK), to whom we express our thanks. It is our hope to continue work at this level in the near future.

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# SESSION II BIOLOGICAL EFFECTS

## BIOLOGICAL EFFECTS OF CHEMICALLY DISPERSED CRUDE OILS IN INSHORE MARINE SEDIMENTS - PRELIMINARY RESULTS FROM BEHAVIOURAL EXPERIMENTS WITH A POST-LARVAL CRUSTACEAN IN THE LABORATORY

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### SUMMARY

Studies following the Buzzards Bay FLORIDA spill in 1969 and the Chedabucto Bay ARROW spill in 1970 demonstrated that spilled oil enters coastal sediments and resides there for considerable periods of time (Blumer and Sass, 1972; Scarratt and Zitko, 1972; Vandermeulen and Gordon, 1976; Sanders et al., 1980). The potential for acute and chronic toxic effects of petroleum hydrocarbons fluxing in and out of sediments is now understood to be a complex function of properties of the hydrocarbons, sediments, overlying waters, sediment-water interface and the exposed organisms. The extent and duration of such effects directly relate to the residence time of specific compounds and fractions (Sanders et al., 1980; Vandermeulen 1982), and specific physiological and behavioural characteristics of the organisms. A considerable scientific effort continues on the fate and effects of oil-derived hydrocarbons in sediments, especially comparing the situation with and without the application of dispersants (Mackay et al., 1981; ASTM, 1982; API, 1983). Some of this effort has addressed the very important question of the survival and settlement of invertebrate larvae over oiled sediments (Vanderhorst and Anderson, pers. comm., Wells 1982).

In our laboratory, we have addressed two fundamental questions on dispersed oil in sediments: a) Is it more toxic, more available, or both, to a post-larval crustacean, in our case lobsters (*Homarus americanus*) living on and in the sediments, compared to oil alone? b) What effect does bioturbation of the oil-dosed sediments have on the residence time and behavioural toxicity of the dispersed oil? Lobsters are an ideal test organism, as they have a planktonic phase, a settling phase, and a settled (benthic) phase within a few weeks of hatching; much is known of their biology, and there is considerable interest in new information on their young stages; they are available and easily kept and worked with; they are also of considerable importance in the Maritime Provinces.

A series of acute experiments have been conducted to identify natural sediments compatible with lobster digging activity, including burrowing, under our laboratory conditions (Wells and Abernethy, 1983). Factors other than oil which influence the digging activity have been identified. Two experiments have established an oil dosing proceedure and have described the hydrocarbon concentrations in the sediment and in water over time, using fluorescence and UV spectroscopy. Experiments are now being conducted with settling fourth-stage lobsters over dosed sediments, repeating the chemistry, and describing the survival, digging behaviour, growth and development of the exposed lobsters. These experiments have all been conducted in plexiglass chambers, in darkness, at 10°C, in flowing filtered natural seawater.

Our paper will present results of these current experiments. Our experiences with sediment behavioural toxicity tests will be described. The control and interpretation of exposure regimes for organisms continually digging and burrowing in artificially contaminated sediments is discussed, with implications for laboratory-based hazard assessments of chemically dispersed oils under temperate and Arctic marine conditions.

### ACKNOWLEDGEMENTS

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# BEHAVIOURAL RESPONSES OF BENTHIC INVERTEBRATES EXPOSED TO DISPERSED CRUDE OIL

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## ABSTRACT

A series of experiments were carried out with the purpose of defining behavioural responses in three species of benthic invertebrates, *Strongylocentrotus droebachiensis* (STR), *Serripes groenlandicus* (SER) and *Mya truncata* (MYA), when exposed to Lago medio crude oil. The dosing protocol was designed to correlate with the 1981 BIOS experimental spill program but relied on tank exposures using a flow-through seawater system on site at Cape Hatt, N.W.T. Oil was added to test systems as an oil/dispersant 10/1 mix at 0.5 to 500 ppm, as well as regimes similar to the field spills. Exposures were static for 6-hour periods. Samples were taken for hydrocarbon analysis of seawater and tissues. Each experiment was followed to a 7-day clearance period.

MYA responded to the addition of dispersed oil by ostial closure and siphon retraction. At high doses, there was a decrease in the effectiveness of mantle and siphon retraction following mechanical stimulation.

SER also exhibited sensitivity to oil by ostial closure and siphon retraction. Emergence out of the sediment occurred at concentrations greater than 100 ppm. Increased locomotion was observed. High doses resulted in latent responses of shell gaping and foot extrusion. An earlier response was extreme closure of the valves, resulting in breakage at the margins. A loss of stimulus responsiveness occurred at the 500 ppm dose with a decrease in the effectiveness of siphon and foot retraction, as well as shell closure when stimulated by touch.

STR showed a rapid onset of behavioural changes at 5 ppm and greater. These included a loss of adherence to substrate and a loss of decoration with shells and seaweed. Spines became rigid at low doses and drooped at higher doses even after the removal of the oil. Tube feet retraction was common. Narcosis was evident with a loss in spine and tube feet responsiveness to mechanical stimuli. A dose-response relationship was demonstrated. Recovery was good except at the 500 ppm dose.

Limited observations were carried out to assess the effects of the dispersant Corexit, and to differentiate sensitivities of small and large individuals. All three species took up petroleum hydrocarbons at a level which was dose-related. STR continued to load soft tissues with hydrocarbon transferred from the external body surface even during the clearing periods.

The behavioural data are interpreted in the context of individual survival, of potential for hydrocarbon loading, and generally in relation to the BIOS experimental spill data.

## INTRODUCTION

The invertebrate biota inhabiting the Arctic seafloor has been shown to be affected by petroleum. Polychaetes, isopods, and amphipods showed a number of negative responses when exposed (Atlas et al., 1978; Percy, 1977). These included an inability to recolonize contaminated sediments, increased respiration, and death. Observations made during the experimental spills of the Baffin Island Oil Spill (BIOS) project demonstrated that bivalves and urchins were affected, showing emergence out of the sediment and apparent narcosis (Cross and Thomson, 1982).

There is little doubt that acute exposures can have a significant effect on benthic biota. Depending on the location, this may have direct effects on other components of the ecosystem. If the benthic population becomes reduced in feeding areas for marine mammals such as walrus (*Odobenus marinus*) or for seabirds such as eiders (*Somateria* spp.), the results may be locally significant.

The 1981 experimental spill study was successful in differentiating the short-term effects of a dispersed oil spill from that of an untreated oil discharge. A large amount of important information was generated by the study in this regard. A consequence of the limitations of an experimental study carried out in the field, however, is that it was not possible to account for and control all impinging variables. A full assessment of fate and effects has to use extrapolation and interpretation of the data generated. The study described here will attempt to define, in a controlled manner, a number of behavioural effect indices which were suggested in the 1981 BIOS field spill, as well as describe more broadly the responses of Arctic marine benthos to oil.

## METHODS AND MATERIALS

### Location

The field portion of this study was carried out at Cape Hatt in Eclipse Sound, N.W.T. (72°28'N, 79°50'W), at the location of the 1981 Baffin Island Oil Spill study. On-site laboratory experiments were designed to investigate the behavioural responses of three selected species of benthic invertebrates to chemically dispersed crude oil. These tank studies were conducted on the shores of Cape Hatt during the period of August through early September 1982.

### Experimental Design

**Holding and Species Parameters.** A flow-through system was constructed on-site to provide a number of 50 L aquaria simultaneously with a continuous flow of seawater at a rate of approximately 100 mL/min per tank. Water originated offshore from an 8 m water depth (high tide), taken 1 m above the bottom sediment. During dosing periods, the flow-through system was temporarily interrupted and individual circulators were used on each test and control tank to recirculate the total water volume at a rate of 8 L/min.

Temperature and salinity were verified regularly and were found to be 6 ± 1°C and 26 ± 3 °/oo, respectively, throughout the experimental period. This was similar to conditions recorded in offshore waters where the test species were collected. Further normalization of holding conditions was approached by the use of subdued natural lighting in the onshore laboratory.

The three test species selected were two filter-feeding bivalves, *Mya truncata* and *Serripes groenlandicus*, and a surface deposit-feeder, the green sea urchin *Strongylocentrotus droebachiensis*. All three species were collected by divers in 7 m water depths off the western shore of Ragged Island, a site near Cape Hatt but removed from potential oil contamination during the 1981 experimental spill. The test animals were transferred to the field laboratory, where they were acclimated in the flow-through seawater system for at least 7 days prior to the exposure studies. Mortalities during this acclimation period were less than 3%. Fresh seaweed (*Laminaria* sp.) and broken shell material were supplied regularly to the urchins during the pre-exposure period. *Serripes groenlandicus* were kept in a 10 cm layer of washed and sifted coarse beach sand, while both *M. truncata* and *S. droebachiensis* were held without sediment in the test tanks.

Except as noted below, the three species were of a medium size range, as identified in previous BIOS studies (Cross and Thomson, 1981). *Mya truncata* were 4.6 + 0.4 cm, *S. groenlandicus* were 4.3 + 0.6 cm, and urchins were 4.6 + 0.5 cm. One test series also used small and large individuals (*M. truncata*, 2.7-4.4 + 0.3 cm; *S. groenlandicus*, 2.7-5.1 + 0.4 cm; *S. droebachiensis*, 3.0-5.4 + 0.3 cm). Holding densities were calculated to not exceed field densities and were limited to 20 individuals of medium size for each species per 50 L aquarium.

**Dosing Protocols.** Dispersed oil concentrations were prepared by dilution of a stock oil/dispersant mixture. This was prepared by vortex stirring of the BIOS-stock aged Lago medio crude oil with Corexit 9527, 1:10, in seawater, as a 25,000 ppm solution. All concentrations are expressed on a basis of weight of crude oil.

Eight experimental conditions were tested, as outlined in Table 1. In all instances, the dosing procedure was similar, with concentrations, exposure times and number or size of animals being varied in accordance with the intent of the test. Single 6-hour exposures were carried out to assess dose-responses or experimental variables. Sequential doses (three at 6 h each) were designed to correlate with conditions recorded in Bays 9 and 10 after the field spill experiment. Corexit was tested alone at one concentration. Other experiments were carried out to differentiate the effect of a probable partial loss of volatiles from the dispersed oil during the exposure period. A post-exposure period of 7 days was used to assess recovery. Controls for each species were monitored concurrently with the exposure experiments.

**Sampling Scheme.** Water samples were taken from each exposure system during the first 5-10 min, and approximately 2, 4 and 6 h after the addition of each oil dispersion. A further sample was taken 1 h and 12 h after the exposure periods, when the tanks had undergone a rapid flushing with clean seawater. These 50 mL samples were analyzed for hydrocarbons by real-time fluorometry. A few additional 10 mL water samples were taken during the exposures for gas chromatographic analysis.

Samples for tissue hydrocarbons were taken at the end of the exposure periods (6 or 18 h) and at 7 d. The soft tissues of five individuals of each species were removed and pooled as a single sample for each time period. The tissues were wrapped in aluminum foil, sealed in Whirl-paks, and frozen.

All glassware and instruments used for hydrocarbon residue samples were prerinsed and dried with high purity hexane-methylene chloride solvent.

TABLE I DOSING PROTOCOL

| Experimental Condition | Concentrations (ppm) | Exposure Time (h) | Test Organisms[a] |
|---|---|---|---|
| Single exposure | 0,0.5,5.0,50,100,500 | 6 | MYA<br>SER<br>STR |
| Sequential exposure Bay 10 simulation | 0.5/5.0/0.2 | 6 each | MYA<br>SER<br>STR |
| Sequential exposure Bay 9 simulation | 10/100/5.0 | 6 each | MYA<br>SER<br>STR |
| Single exposure (covered and uncovered comparisons) | 250 | 6<br>6 | STR<br>STR |
| Sequential exposure (covered and uncovered comparisons) | 10/100/5.0 | 6 each | MYA<br>SER<br>STR |
| Single exposure (size comparisons) | 250 | 6 | MYA<br>SER<br>STR |
| Single exposure (predation test) | 250 | 6 | SER |
| Corexit exposure | 50 | 6 | MYA<br>SER<br>STR |

[a] SER = *Serripes groenlandicus* MYA = *Mya truncata* STR = *Strongylocentrotus droebachiensis*

n = 20 per test, except 15 for size comparison tests.

**Analyses.** Water samples were analyzed by real-time fluorometry and by gas chromatography on stored samples. The fluorometric method used a Turner model 240 flow-through fluorometer, calibrated and blank adjusted before and during use. Dispersed Lago medio crude was used for calibration. All readings were carried out in the linear range of the fluoresence calibration, at times necessitating dilution of test samples with seawater. Reproducibility of duplicate samples was found to be 5% or less.

Water analysis by gas chromatography was used in a limited manner to obtain preliminary data on hydrocarbon fraction composition in the test systems and to serve as a check on total oil concentrations determined by fluorometry.

The analyses were carried out under contract by Seakem Oceanography Ltd., using a Hewlett-Packard Model 5830A gas chromatograph, equipped with a J & W fused silica column with a SE-30 stationary phase. Standard methods were employed for the characterization of hydrocarbons in hexane extracts of the 10 mL water samples. Hydrocarbon concentrations were expressed as ppm of crude oil, calculated on the basis of the C-21 to C-24 alkane peaks relative to an internal standard (cetylbenzene).

Tissue hydrocarbon residues were analyzed as follows. Extraction of the samples was carried out according to the method of Engelhardt et al. (1982). Fused silica capillary GC ($GC^2$) of an aromatic hydrocarbon fraction ($f_2$) obtained through alumina/silicic acid fractionation of the total extract was used (Boehm et al., 1982). Naphthalene (N), methyl ($C_1$) naphthalenes, ethyl/dimethyl ($C_2$) naphthalenes and trimethyl ($C_3$) naphthalenes were quantified. The ratio of $C_3N$ to total aromatics, and in turn the ratio of total aromatics to total oil (as determined by a combination of electrobalance gravimetric measurement on total oil and aromatic ($f_2$) fraction and total $C_3N$ peak area to total $f_2$ peak area) were used to convert $C_3N$ to "total oil" values for neat oil. As each sample was analyzed by $GC^2$, the total amounts of N, $C_1N$, $C_2N$, $C_3N$, and alkylated benzenes were obtained directly from the $GC^2$ trace. The $C_3N$:total oil conversion was used to arrive at the "total oil" values reported for the animals.

A variety of behavioural responses were recorded and quantified. The choice of particular behavioural indices of petroleum effect was based on extensive observations of the three species during the acclimation periods, and was predicated on being both quantifiable and significant to the survival of the individual. Characteristics of the index behavioural responses are detailed in Table 2.

TABLE 2 BEHAVIOURAL RESPONSES OF *MYA TRUNCATA*, *SERRIPES GROENLANDICUS* AND *STRONGYLOCENTROTUS DROEBACHIENSIS* EXPOSED TO CRUDE OIL DISPERSIONS

| Target species | Behavioural Responses | Description |
|---|---|---|
| *Strongylocentrotus droebachiensis* | direct observations | |
| | cover | shell fragments and pieces of algae cover test on aboral surface |
| | attachment | attachment to glass of aquarium floor and sides by tube feet |
| | spine droop | depression of spine downward along test surface |
| | spine rigidity | "pincushion" orientation and loss of flexibility |
| | curling of tube feet | aboral tube feet showing curling of distal ends |
| | retraction of tube feet | aboral tube feet not existent |
| | stimulus response | |
| | tube feet | tube foot retraction following mechanical stimulus laterally on test |
| | spine | re-orientation towards source of mechanical stimulus laterally on test |
| *Mya truncata* | direct observations | |
| | ostial closure | closure of both inhalent and exhalent siphons |
| | siphon retraction | retraction of siphon to 1/2 or less of normal extended length |
| | stimulus response | |
| | siphon | siphon retraction following mechanical stimulus to siphon |
| | mantle | retraction of mantle and closure of shell following mechanical stimulus of mantle edge |
| *Serripes groenlandicus* | direct observation | |
| | buried | burial to depth where ostia are exposed |
| | ostial closure | closure of one or both ostia |
| | mantle gape | mantle edges not closed and shell gaping |
| | stimulus response | |
| | siphon | siphon retraction following mechanical stimulus to siphon |

Quantitation of these responses was on the basis of proportion of the test population (n = 20) showing a change as related to exposure concentration and elapsed time. A standard point of comparison was the time at which 50% of the starting population showed a response ($ET_{50}$). Recovery was assessed as that point in elapsed time at which the proportion of animals showing the response had returned to pre-exposure levels. The reported $ET_{50}$ and recovery time values were obtained from data plots made for each species and exposure test, comparing percentage of test population showing the response to elapsed time.

Behavioural changes in addition to quantified responses were also described. Such changes tended to be less consistent, or could not be observed to involve at least 50% of the test population at any concentration.

## RESULTS

### Exposure Concentrations

A comparison of nominal and fluorometry measured concentrations of crude oil hydrocarbons in the various test systems showed deviations of as much as 50% from the expected starting concentrations. The deviation was usually an increase in both single exposure (Table 3) and sequential exposure tests (Table 4). In all instances, the measured concentrations declined over the 6-h periods of static recirculated exposure to an average of two-thirds of starting concentrations. Subsequent extrapolations of concentrations to 6 h averages indicated that total exposures were very similar to nominal concentrations.

A small number of water samples were assessed by gas chromatography (GC) for both total oil concentration and fraction characteristics. Quantitation using C-21 to C-24 alkanes and an internal standard showed similar concentrations of oil in water as assessed by both methods. Both fluorometry and GC demonstrated similar declines in total oil concentration whether the systems were run covered or uncovered, as was the case for the majority of the tests.

### Behavioural Responses

**Mya truncata.** This species responded to the presence of oil somewhat inconsistently, especially at the lower concentrations. Ostial closure and siphon retraction were common at concentrations above 10 ppm (Table 5; Figure 1). Loss of response capability to mechanical stimulation by retraction of the siphon or mantle was noted at concentrations of 50 ppm and above. This response tended to be latent. Recovery was rapid at low-level exposures even during the dosing period. Exposure to higher concentrations required longer recovery times. Corexit at 50 ppm elicited all four quantitated behavioural changes soon after exposure. Recovery times, however, were much shorter, with a return to normal behaviour within 1 d of the exposure.

The sequential dosing experiments suggested that responses were delayed relative to single exposures. These responses often did not occur during the period of highest concentration (for example, the 100 ppm phase (Table 6)); recovery required 1 to several days, as in the case of the single 100 ppm exposures. Neither size differences nor the effect of covering the exposure tanks could be differentiated in the *Mya truncata* tests.

Other behavioural changes were observed to occur as a consequence of oil exposure. At low concentrations, or early in the exposure periods, the diameters of siphon ostia tended to be increased. Occasional extensions of the foot were common. Elongation of the siphon was observed at high concentrations, especially late in the post-exposure period. No lethality was observed.

TABLE 3 PETROLEUM HYDROCARBON CONCENTRATIONS IN WATER OF SINGLE TEST SYSTEMS, COMPARING NOMINAL CONCENTRATIONS TO VALUES DETERMINED BY REAL-TIME FLUOROMETRY AND BY GAS CHROMATOGRAPHIC ANALYSIS OF SELECTED SAMPLES

| Nominal Concentration[a] (ppm) | Time[b] (hours) | Test Species[c] | Measured Concentration (ppm) | |
|---|---|---|---|---|
| | | | Fluorometry | Gas Chromatography |
| 0 | 0.1 | MYA | nd | - |
| | | SER | nd | - |
| | | STR | nd | - |
| | 12 | MYA | nd | - |
| | | SER | nd | - |
| | | STR | nd | - |
| 0.5 | 0.1 | MYA | 0.70 | - |
| | | SER | 0.55 | - |
| | | STR | 0.80 | - |
| | 6 | MYA | nd | - |
| | | SER | 0.40 | - |
| | | STR | 0.40 | - |
| | 12 | MYA | nd | - |
| | | SER | nd | - |
| | | STR | nd | - |
| 5.0 | 0.1 | MYA | 8.0 | - |
| | | SER | 8.7 | - |
| | | STR | 7.8 | - |
| | 6 | MYA | 6.0 | - |
| | | SER | 6.4 | - |
| | | STR | 6.8 | - |
| | 12 | MYA | nd | |
| | | SER | nd | |
| | | STR | nd | |
| 50 | 0.1 | MYA | 60 | - |
| | | SER | 60 | - |
| | | STR | 64 | - |
| | 6 | MYA | 26 | 26 |
| | | SER | 22 | - |
| | | STR | 23 | - |
| | 12 | MYA | nd | - |
| | | SER | nd | - |
| | | STR | nd | - |
| 100 | 0.1 | MYA | 140 | - |
| | | SER | 128 | - |
| | | STR | 136 | - |
| | 6 | MYA | 86 | 75 |
| | | SER | 80 | 86 |
| | | STR | 78 | 44 |
| | 12 | MYA | nd | - |
| | | SER | nd | - |
| | | STR | nd | - |
| 250 | 0.1 | MYA | 380 | - (295)[d] |
| | | SER | 350 | - (133) |
| | | STR | 310 (350) | 320 (183) |

TABLE 3 PETROLEUM HYDROCARBON CONCENTRATIONS IN WATER OF SINGLE TEST SYSTEMS, COMPARING NOMINAL CONCENTRATIONS TO VALUES DETERMINED BY REAL-TIME FLUOROMETRY AND BY GAS CHROMATOGRAPHIC ANALYSIS OF SELECTED SAMPLES (cont'd)

| Nominal Concentration[a] (ppm) | Time[b] (hours) | Test Species[c] | Measured Concentration (ppm) | |
|---|---|---|---|---|
| | | | Fluorometry | Gas Chromatography |
| 250 | 6 | MYA | 225 | - (96) |
| | | SER | 225 | - (86) |
| | | STR | 200 (225) | 269 (153) |
| 500 | 6 | MYA | 310 | 307 |
| | | SER | 290 | - |
| | | STR | 290 | - |
| | 12 | MYA | nd | - |
| | | SER | nd | - |
| | | STR | nd | - |

[a] Calculated as dilution of Lago medio crude-Corexit stock dispersion.

[b] Elapsed time from start of 6-h continuous exposure period.

[c] MYA - *Mya truncata*; SER - *Serripes groenlandicus*; STR - *Strongylocentrotus droebachiensis.*

[d] Numbers in parentheses are concentration values from duplicate tests in which exposure systems were covered.

nd = not detectable

- = no data collected

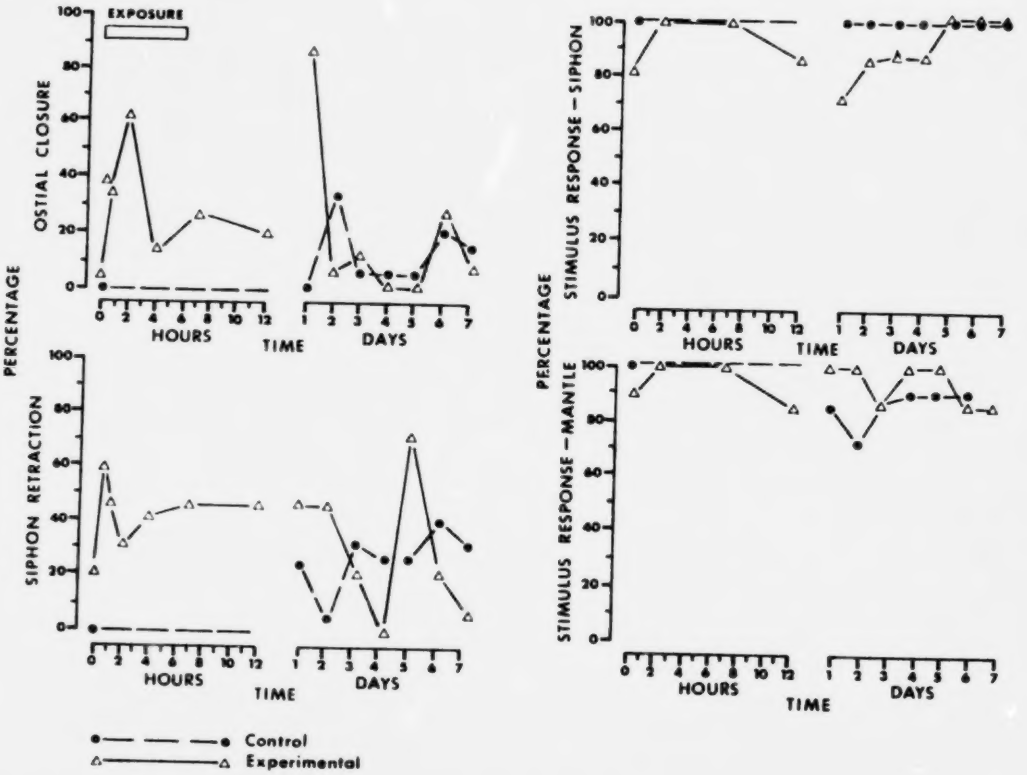

FIGURE 1 SELECTED BEHAVIOURAL RESPONSES OF *MYA TRUNCATA* TO 50 PPM DISPERSED OIL

TABLE 4 PETROLEUM HYDROCARBON CONCENTRATIONS IN WATER OF SEQUENTIAL TEST SYSTEMS, COMPARING NOMINAL CONCENTRATIONS TO VALUES DETERMINED BY REAL-TIME FLUOROMETRY AND BY GAS CHROMATOGRAPHIC ANALYSIS OF SELECTED SAMPLES

| Nominal Concentrations[a] (ppm) | Time[b] (hours) | Test Species[c] | Measured Concentration (ppm) | | | |
|---|---|---|---|---|---|---|
| | | | Fluorometry | | Gas Chromatogrpahy | |
| | | | ncv[d] | cv | ncv | cv |
| 0.5/5/0.2 | 0.1 | MYA | 0.40 | | nd | |
| | | SER | 0.35 | | - | |
| | | STR | 0.40 | | - | |
| | 6 | MYA | 0.20 | | nd | |
| | | SER | nd | | - | |
| | | STR | nd | | - | |
| | 6.2 | MYA | 10 | | nd | |
| | | SER | 5.0 | | - | |
| | | STR | 6.5 | | - | |
| | 12 | MYA | - | | nd | |
| | | SER | 5.0 | | - | |
| | | STR | 4.0 | | - | |
| | 12.2 | MYA | 1.2 | | nd | |
| | | SER | 1.1 | | - | |
| | | STR | 0.65 | | - | |
| | 18 | MYA | 1.0 | | nd | |
| | | SER | 1.0 | | - | |
| | | STR | 0.80 | | - | |
| 10/100/5 | 0.1 | MYA | 12, 6.5 | 7.5 | nd | nd |
| | | SER | 10, 8.0 | 8.0 | - | - |
| | | STR | 10, 7.5 | 8.0 | - | - |
| | 6 | MYA | 8.5, 6.5 | 6.5 | nd | nd |
| | | SER | 10, 5.0 | 6.2 | - | - |
| | | STR | 6.5, 5.0 | 5.0 | - | - |
| | 6.2 | MYA | 150, 80 | 65 | 73, 159 | 130 |
| | | SER | 150, 80 | 75 | - | - |
| | | STR | 100, 90 | 65 | - | - |
| | 12 | MYA | 95, 65 | 50 | 110, 171 | 105 |
| | | SER | 70, 50 | 50 | - | - |
| | | STR | 65, 50 | 50 | - | - |
| | 12.2 | MYA | 10, 4.0 | 6.5 | nd | nd |
| | | SER | 8.5, 5.0 | 6.5 | - | - |
| | | STR | 8.5, 5.0 | 6.5 | - | - |
| | 18 | MYA | 7.0, 4.0 | 4.0 | nd | nd |
| | | SER | 7.0, 3.7 | 4.0 | - | - |
| | | STR | 7.5, 3.7 | 4.0 | - | - |

[a] Calculated as three dilutions of Lago medio crude-Corexit stock dispersions, presented sequentially.

[b] Elapsed time from start of three sequential exposure periods, each of 6-hour duration.

[c] MYA - *Mya truncata*; SER - *Serripes groenlandicus*; STR - *Strongylocentrotus droebachiensis*.

[d] ncv - tanks not covered during exposure period; cv - tanks covered during exposure period.

nd = not detectable; - = no data collected

TABLE 5 BEHAVIOURAL RESPONSES OF *MYA TRUNCATA* EXPOSED TO CRUDE OIL DISPERSIONS IN SINGLE TESTS

| Exposure[a] Condition | Ostial Closure | Siphon Retraction | Stimulus Response - Siphon | Stimulus Response - Mantle |
|---|---|---|---|---|
| $ET_{50}$ | | | | |
| **Oil** | | | | |
| 0.5 | NC | 3 h | NC | NC |
| 5.0 | <0.5 h | NC | NC | 5 d |
| 50 | 1 h | 1 h | NC | NC |
| 100 | 0.5 h | 0.5 h | NC | 1 d |
| 250 (cv, sml) | - | - | 2 d | - |
| 250 (cv, lg) | <2 h | - | - | - |
| 500 | - | - | 12 h | 6 h |
| **Corexit** | | | | |
| 50 | <0.5 h | 6 h | <0.5 h | <0.5 h |
| RECOVERY | | | | |
| **Oil** | | | | |
| 0.5 | NC | 6 h | NC | NC |
| 5.0 | 1 h | NC | NC | 6 d |
| 50 | 2 d | 3 d | NC | NC |
| 100 | 12 h | 3 d | NC | 2 d |
| 250 (cv, sml) | 1 d | 1 d | >2 d | 1 d |
| 250 (cv, lg) | 1 d | 1 d | 5 d | 1 d |
| 500 | 2 d | 5 d | 1 d | 1 d |
| **Corexit** | | | | |
| 50 | 1 d | 1 d | 4 h-1 d | 4 h-1 d |

[a] 6 Hours of exposure to Lago medio crude oil or Corexit 9527 dispersions, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv; animal size medium except where noted as sml or lg.

NC = no change

- = no data, due to inacessibility of animals because of covered system or to inability to observe behavioural change in dispersion-clouded water

TABLE 6 BEHAVIOURAL RESPONSES OF *MYA TRUNCATA* EXPOSED TO CRUDE OIL DISPERSIONS IN SEQUENTIAL TESTS

| Exposure[a] Condition | Ostial Closure | Siphon Retraction | Stimulus Response - Siphon | Stimulus Response - Mantle |
|---|---|---|---|---|
| ET$_{50}$ | | | | |
| 0.5/5.0/0.2 | NC | NC | NC | NC |
| 10/100/5.0 | 3 h | 6 h | 1 d | 13 h |
| 10/100/5.0 | 7 h | NC | - | - |
| 10/100/5.0 (cv) | 7 h | NC | - | - |
| RECOVERY | | | | |
| 0.5/5/0.2 | NC | NC | NC | NC |
| 10/100/5 | 1 d | 1 d | 5 d | 1 d |
| 10/100/5 | 15 h | NC | - | - |
| 10/100/5 (cv) | 18 h | NC | - | - |

[a] 18 Hours of exposure to Lago medio crude oil dispersions, given in three sequential concentrations of 6 hours each, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv.

NC = no change

- = no data

**Serripes groenlandicus.** At concentrations below 50 ppm, only ostial closure occurred as a response to oil (Table 7; Figure 2). Ostial closure showed a concentration-response relationship from 0 to 100 ppm, the time to affect closure decreasing with increased concentration. A discontinuity in this response occurred above 100 ppm, where ostia were closed in 50% of the test population only after several hours. At 250 ppm, both emergence from the sediment and an increased gaping of the mantle opening (and shell) became major responses. At 500 ppm, all behavioural indices were affected, with biphasic responses noted in mantle/shell gape, foot protrusion, and reaction to mechanical stimuli. The second phase of these responses was latent, occurring after the exposure period. Lethality as well was latent at 500 ppm, with an ET$_{50}$ of 6 d. Recovery took 1 to several days, suggesting a dose response of increased recovery time with increasing concentrations. The data on the effect of differential sizes of test organisms to 250 ppm exposure were inconclusive.

Exposure to 50 ppm of Corexit resulted in emergence from the sediment, ostial closure, and mantle gape responses similar to the 500 ppm dispersed oil dose. Time to recovery from this exposure was shorter, however, and there was no lethality.

The 18-h three-phase exposure regime resulted in unique response patterns (Table 8). An initial 6-h exposure to 0.5 or 10 ppm resulted in an enhanced response to the mid-sequence high concentration, as compared to single doses of 5 and 100 ppm. Recovery as well was markedly delayed in the sequential exposure tests. Only the 500 ppm exposure resulted in lethality. The survivors recovered normal behaviour patterns. The use of tank covers to minimize evaporative hydrocarbon loss did not consistently alter the responses to sequential exposures. Most indices remained similar.

An additional response had to be inferred from the observations of ostial closure. Siphon retraction was a probable accompanying response which could not be quantified given the normal attitude of the bivalve. This attitude is characterized by burial to various depths in the sediment with only the tip of the siphon and ostia showing. Siphon retraction and forceful closure were probable occurrences at concentrations of 50 ppm and greater, as evidenced by a high incidence of shell damage. Individuals which emerged from the sediment tended to be cracked along the margins of their valves. At times this involved as much as one-third of the shell surface, exposing soft tissues. Forceful closure of the two valves was an additional latent response during both the 500 ppm single dose and the 10/100/5 ppm sequential exposure. Shell damage resulted from tight opposition of the valves, pinching an extruded foot. Increased locomotion occurred as a result of the extruded foot contacting the sediment and straightening rapidly to propel the shell. Locomotion was erratic and was observed primarily in emerged individuals early on during exposure to single concentrations of 250 and 500 ppm, and to the serial 10/100/5 ppm exposure. The style of locomotion was similar but was observed only rarely during the pre-exposure period.

TABLE 7 BEHAVIOURAL RESPONSES OF *SERRIPES GROENLANDICUS* EXPOSED TO CRUDE OIL DISPERSIONS IN SINGLE TESTS

| Exposure[a] Condition | Emergence | Ostial Closure | Mantle Gape | Foot Protrusion | Stimulus Response - Siphon | Lethality |
|---|---|---|---|---|---|---|
| ET$_{50}$ | | | | | | |
| **Oil** | | | | | | |
| 0.5 | NC | 6 h | NC | NC | NC | NC |
| 5.0 | NC | 1 h | NC | NC | NC | NC |
| 50 | 6 h | <0.5 h | NC | NC | NC | NC |
| 100 | 12 h | <0.5 h | NC | NC | NC | NC |
| 250 (cv, sml) | 6 h | <5 h | 1 d[b] | NC | - | NC |
| 250 (cv, lg) | 6 h | <6 h | 3d[b] | NC | - | NC |
| 500 | 4 h | 3 h | <0.5 h,<br>3 d | <0.5 h,<br>1 d | <0.5 h,<br>7 d | 6 d |
| **Corexit** | | | | | | |
| 50 | 4 h | 3 h | 4 h | NC | - | NC |
| RECOVERY | | | | | | |
| **Oil** | | | | | | |
| 0.5 | NC | 1 d | NC | NC | NC | NC |
| 5.0 | NC | 2 d | NC | NC | NC | NC |
| 50 | 3 d | 2 d | NC | NC | NC | NC |
| 100 | 3 d | 2 d | NC | NC | NC | NC |
| 250 (cv, sml) | 5 d | 5 d | 5 d | NC | - | NC |
| 250 (cv, lg) | 3 d | 6 d | 5 d | NC | - | NC |
| 500 | >7 d | 6 d | 1 d>,<br>7 d | 2 h,<br>7 d | 3 d | - |
| **Corexit** | | | | | | |
| 50 | 2 d | 2 d | 2 d | NC | - | NC |

[a] 6 Hours of exposure to Lago medio crude oil or Corexit 9527 dispersions, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv; animal size medium except where noted as sml or lg.

[b] Indicates the maximum response shown by less than 50% of starting test population, generally 20-40%.

NC = no change.

- = no data, usually because of use of a covered test system.

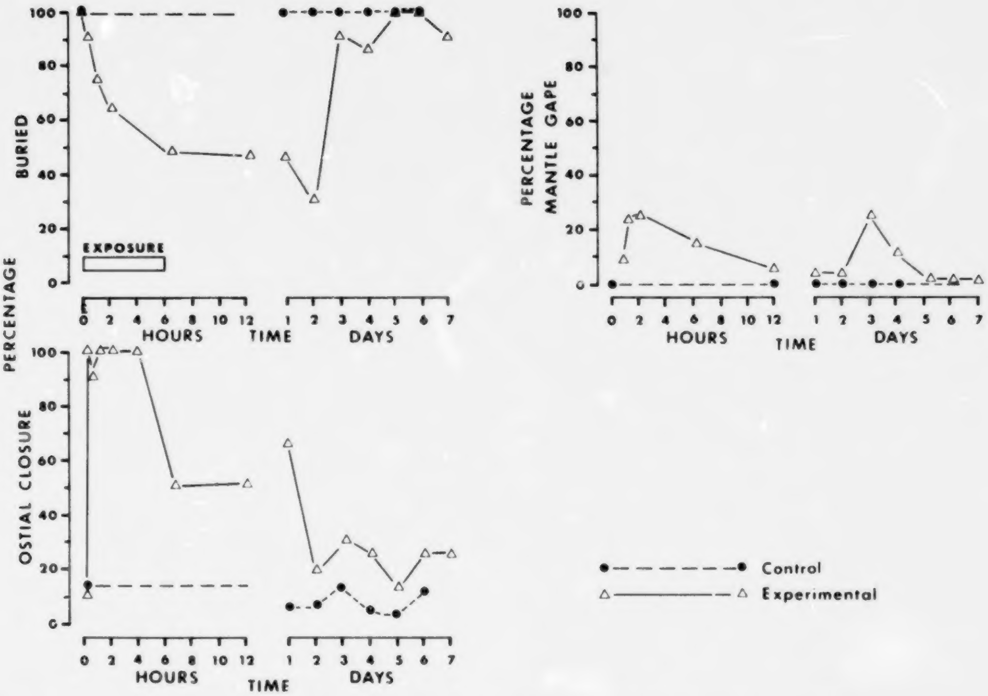

FIGURE 2 SELECTED BEHAVIOURAL RESPONSES OF *SERRIPES GROENLANDICUS* TO 50 PPM DISPERSED OIL

TABLE 8 BEHAVIOURAL RESPONSES OF *SERRIPES GROENLANDICUS* EXPOSED TO CRUDE OIL DISPERSIONS IN SEQUENTIAL TESTS

| Exposure[a] Condition | Emergence | Ostial Closure | Mantle Gape | Foot Protrusion | Stimulus Response - Siphon | Lethality |
|---|---|---|---|---|---|---|
| ET50 | | | | | | |
| 0.5/5/0.2 | 18 h | 6 h | NC | NC | NC | NC |
| 10/100/5 | 13 h | <0.5 h | 7 h, 2 d | 7 h, 1 d | NC | |
| 10/100/5 | 18 h | <0.5 h | 7 h, 2 d | 10 h | 7 h | NC |
| 10/100/5 (cv) | 14 h | 1 h | 7 h, 2 d | 0.5 h | - | NC |
| RECOVERY | | | | | | |
| 0.5/5/0.2 | 2 d | 6 d | NC | NC | NC | NC |
| 10/100/5 | >7 d | 5 d | 13 h | 12 h, 2 d | NC | NC |
| 10/100/5 | 6 d | 3 d | 8 h, >7 d | 13 h | 3 d | NC |
| 10/100/5 (cv) | 4 d | 1 d | 8 h, >7 d | 2 h | 2 d | NC |

[a] 18 Hours of exposure to Lago medio crude oil dispersions, given in three sequential concentrations of 6 hours each, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as CV.

NC = no change

- = no data

**Strongylocentrotus droebachiensis.** The urchin was the most responsive benthic species examined in terms of the number of behavioural indices affected by oil. The most sensitive response was the loss of covering material as the aboral tube feet released pieces of macro algae and shell fragments (Table 9; Figure 3).

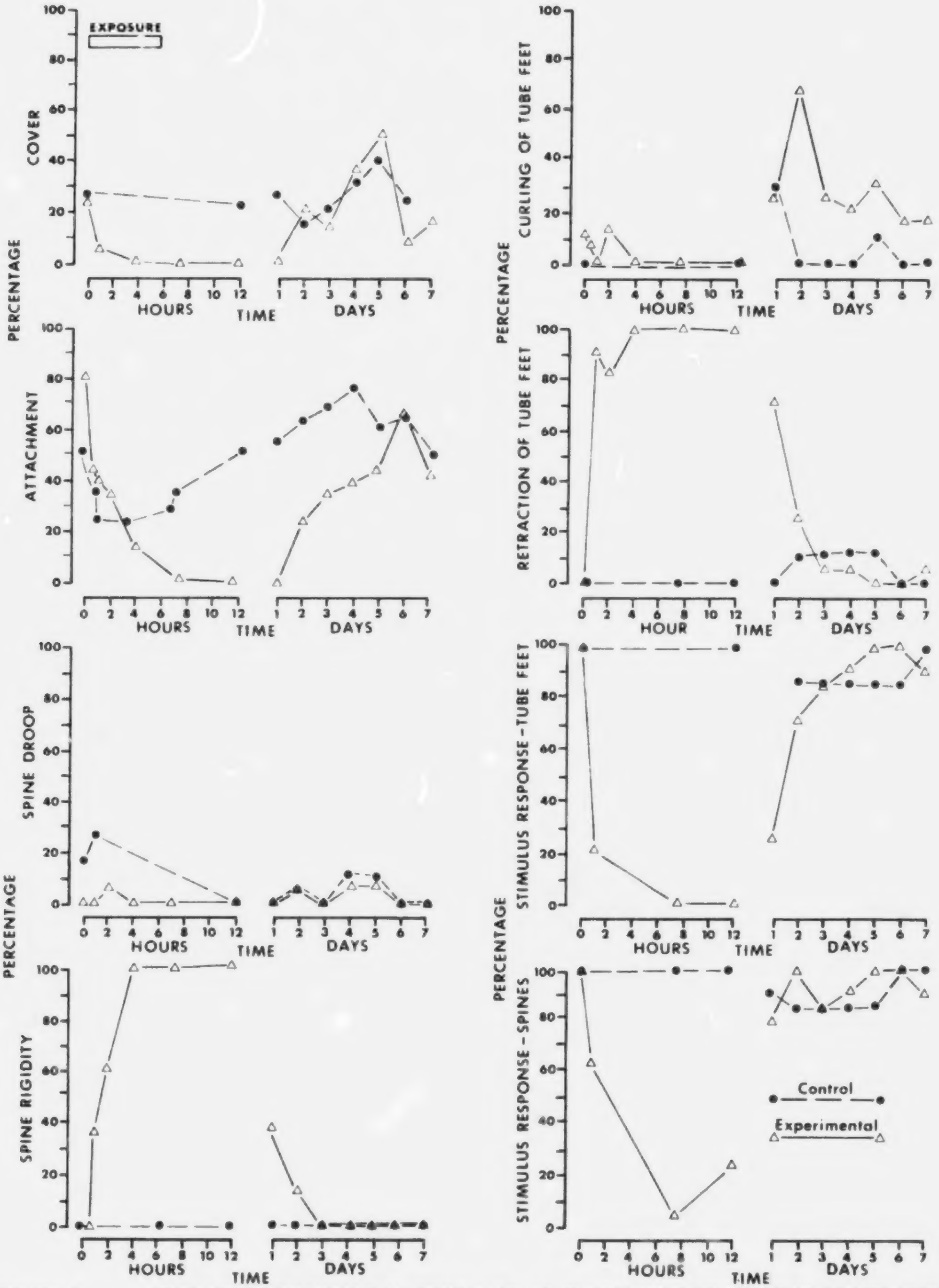

FIGURE 3 SELECTED BEHAVIOURAL RESPONSE OF *STRONGYLOCENTROTUS DROEBACHIENSIS* TO 50 PPM DISPERSED OIL

TABLE 9 BEHAVIOURAL RESPONSES OF *STRONGYLOCENTROTUS DROEBACHIENSIS* EXPOSED TO CRUDE OIL DISPERSIONS IN SINGLE TESTS

| Exposure Condition[a] | Loss of Cover | Loss of Attachment Ability | Spine Droop | Spine Rigidity | Curling of Tube Feet | Retraction of Tube Feet | Stimulus Response Tube Feet | Stimulus Response Spines | Lethality |
|---|---|---|---|---|---|---|---|---|---|
| ET50 | | | | | | | | | |
| **Oil** | | | | | | | | | |
| 0.5 | NC | NC | 8 h[b] | NC | 1 h | 1 h[b] | NC | NC | NC |
| 5.0 | - | NC | 4 h | 3 h | 4 h | 4 h | 5 h | 5 h | NC |
| 50 | <1 h | 3 h | NC | 2 h | 2 d | <1 h | <1 h | 2 h | NC |
| 100 | 2 h | 3 h | - | 3 h | 2 d | <1 h | (2 h) | (2 h) | NC |
| 250 | <0.5 h | <0.5 h | 0.5 h, 1 d | <0.5 h | 0.5 h, 2 d | 1 h | - | - | NC |
| 250 (cv) | <0.5 h | 1 h | 0.5 h, 1 d | <0.5 h | 2 d | <0.5 h | - | - | NC |
| 250 (cv,sml) | 1 h | 1 h | <0.5 h | <0.5 h | <0.5 h, 3 d | <0.5 h | - | - | NC |
| 250 (cv,lg) | 1 h[b] | 1 h | <0.5 h, 1 d | 0.5 h | <0.5 h, 3 d | <0.5 h | - | - | NC |
| 500 | <0.5 h | 1 h | 1 d | <0.5 h | 2 d | - | <1 h | <1 h | 3 d |
| **Corexit** | | | | | | | | | |
| 50 | NC | <0.5 h | <0.5 h[b] | <0.5 h[b] | NC | - | NC | NC | NC |
| RECOVERY | | | | | | | | | |
| **Oil** | | | | | | | | | |
| 0.5 | NC | NC | 2 d | NC | 12 h | NC | NC | NC | NC |
| 5 | 3 d | NC | NC | 1 d | 1 d | 2 d | 1 d | 2 d | NC |
| 50 | 4 d | 3 d | NC | 2 d | 3 d | 3 d | 4 d | 2 d | NC |
| 100 | 4 d | 3 d | NC | 2 d | 4 d | 3 d | 2 d | 2 d | NC |
| 250 | 3 d | >4 d | 4 d | 1 d | 4 d | 2 d | 2 d | 1 d | NC |
| 250 (cv) | 3 d | 4 d | 4 d | 2 d | 7 d | 3 d | 3 d | 1 d | NC |
| 250 (cv,sml) | 3 d | 5 d | 1 h | 3 d | 1 h, 5 d | 3 d | 3 d | 1 d | NC |
| 250 (cv,lg) | 3 d | 4 d | 1 h, 3 d | 2 d | 1 h, 5 d | 3 d | 3 d | 1 d | NC |
| 500 | 3 d | Nil | Nil | 2 d | 7 d | 5 d | >5 d | >4 d | Nil |
| **Corexit** | | | | | | | | | |
| 50 | NC | 12 h | 2 h | 2 h | NC | - | NC | NC | NC |

[a] 6 Hours of exposure to Lago medio crude oil or Corexit 9527 dispersions, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv; animal size medium except where noted as sml or lg.

[b] Indicates that maximum response shown by less than 50% of starting test population, generally 20-40%.

NC = no change; - = no data.

Loss of covering showed a concentration response beginning within 4 h at 10 ppm (Table 10) and occurring much earlier at higher concentrations. Loss of ability by the urchins to remain attached to the walls of the aquaria with their tube feet was also a sensitive response to oil and was also dose-related. Recovery of these tube feet functions required 3 to 5 d, irrespective of concentrations to 500 ppm. At 500 ppm, however, there was no recovery of attachment ability within the 7-d experimental period.

TABLE 10 BEHAVIOURAL RESPONSES OF *STRONGYLOCENTROTUS DROEBACHIENSIS* EXPOSED TO CRUDE OIL DISPERSIONS IN SEQUENTIAL TESTS

| Exposure Condition[a] | Loss of Cover | Loss of Attachment Ability | Spine Droop | Spine Rigidity | Curling of Tube Feet | Retraction of Tube Feet | Stimulus Response Tube Feet | Stimulus Response Spines | Lethality |
|---|---|---|---|---|---|---|---|---|---|
| ET$_{50}$ | | | | | | | | | |
| 0.5/5/0.2 | NC | 7 h | 3 h | 1 h | 12 h | 7 h | 7 h | 7 h | NC |
| 10/100/5 | 4 h | 5 h | 0.5 h | 1 h | 1 h | 0.5 h | 2 h | 2 h | NC |
| 10/100/5 | - | 6 h | 5 h | 6 h | 5 h | 6 h | - | - | 7 d |
| 10/100/5 (cv) | - | 6 h | 4 h | 7 h | 3 h | 6 h | - | - | NC |
| RECOVERY | | | | | | | | | |
| 0.5/5/0.2 | NC | 18 h | 13 h | 15 h | 15 h | 18 h | 16 h | 13 h | NC |
| 10/100/5 | 4 d | 3 d | 2 h | 1 d | 6 d | 6 d | 6 d | 6 d | NC |
| 10/100/5 | - | 5 d | >7 d | 1 d | 9 h | 1 d | 1 d | 1 d | Nil |
| 10/100/5 (cv) | - | 5 d | >7 d | 2 d | 13 h | 1 d | 1 d | 2 d | NC |

[a] 18 Hours of exposure to Lago medio crude oil dispersions, given in three sequential concentrations of 6 hours each, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv.

NC = no change

- = no data

Curling and retraction of aboral tube feet was a further response to oil exposure (Table 9). At 250 ppm, the curling of the ostial ends of the tube feet was bi-phasic. Retraction of tube feet occurred rapidly at high doses, although not all tube feet were retracted simultaneously. A small number of oral and aboral tube feet often continued to attach the urchin to the glass surface. The higher the single exposure dose, the longer was the time required for recovery of these two indices, especially that of curling.

Changes in spine behaviour were observed at exposures to 5 ppm and greater; they occurred more rapidly and recovered more slowly with increasing exposure concentration. Drooping of aboral spines at times occurred in two phases, during both exposure and recovery periods. The "pincushion" effect characterizing spine rigidity tended to be a rapid response. Spine attitude recovery was generally more rapid than tube foot recovery.

Exposures to concentrations of 5 ppm and greater resulted in a loss of response capacity to mechanical stimuli, with ET$_{50}$ times decreased from 5 h to less than 1 h (Table 9). Recovery times were not well correlated with exposure concentration, 1 to 5 d or more being required. Spine responsiveness recovered more rapidly than did tube foot responses. A lethal effect was recorded only when spine and tube foot responses to tactile stimulation were unobtainable. A 3-d ET$_{50}$ for lethality was recorded for the 500 ppm single exposure.

Additional observations of *S. droebachiensis* responses to oil were made. Rapid linear movement along the substrate was noted in some instances at 50 to 250 ppm doses during the first few minutes following the addition of dispersed oil to the test systems. Also, a darkening in surface color was a common response to high-level exposures. Shedding of gametes occurred frequently within 2 d of exposure. Spines tended to drop off several days prior to a determination of death in the individual urchin.

No size specific effects were found in urchins. Exposure to 50 ppm of Corexit resulted in loss of adhesion and spine rigidity, but recovery of both functions was much more rapid than for any dispersed oil exposure.

The data shown in Table 10 suggest that 6 h of exposure to 0.5 ppm enhanced the effect of 5 ppm given in a subsequent dose, as compared to a 5 ppm single exposure. Since 10 ppm exposures were effective in eliciting all behavioural changes within a 6-h time period, it was not possible to differentiate the behavioural responses of 100 ppm single and sequential doses. A comparison test between covered and noncovered systems showed that the urchin response and recovery were similar.

### Tissue Hydrocarbons

The results of tissue hydrocarbon determinations are presented in Table 11. Total aromatic concentrations averaged one-third of the total hydrocarbon levels. Total hydrocarbon values were mathematically derived from the sum of alkylbenzenes and naphthalenes, measured from the gas chromatograms, connected by an aromatic ratio of 0.0056. Total oil values were derived from a total aromatic to total oil ratio of 0.37.

*M. truncata* and *S. groenlandicus* tissues had a greater hydrocarbon load than did *S. droebachiensis* tissues when the samples were taken at 6 h of a single exposure, or 18 h of the sequential test. This relationship was reversed for the 7 d samples in which urchin tissue loads were not only greater than those of the bivalves, but also much higher than they were at 6 or 18 h. Urchin tissues additionally showed a greater capacity to take up alkyl benzenes during the dosing period, although the emphasis on these hydrocarbons tended to be gone in 7-d samples. An overview of tissue hydrocarbons demonstrated fractional compositions qualitatively similar to that of Lago medio crude oil (Figure 4).

## DISCUSSION

### Exposure Concentrations

Fluorescence analysis has shown itself to be a useful method for detecting hydrocarbons in water, especially when used as a real-time measure of experimental concentrations. The 0.5 ppm sensitivity limit is useful, since samples do not require any concentrating or other special handling, thereby minimizing procedural losses of volatile hydrocarbons in particular. The GC method, as employed in this phase of the study, generally verified the fluorometry concentrations. Both the covered and uncovered set-ups are likely to have undergone volatile losses. It is probable that the average one-third decline in starting concentration was mainly due to volatile losses. Nonetheless, averaging of measured concentrations over a 6-h exposure period showed values to be very similar to the nominal concentrations.

The choice of the range of exposure concentrations was predicated by the desire to encompass water concentrations of dispersed Lago medio crude as observed in the 1981 field spill. This condition was met by the series of single exposure tests. Closer similarity with the field concentration scenario was accomplished with the three-phase sequential exposure schemes. The 10/100/5 ppm concentration series was similar in level and sequence to what had been observed in Bay 9, the site of the dispersed oil spill, for the 18-h period subsequent to oil release (Green et al., 1982). The 0.5/5/0.2 ppm concentration sequence approximated the levels during the first 18 h post-spill in Bay 10, an area adjacent and down-channel from the dispersed oil spill site. In both the Bay 9 and 10 simulations, flushing with clean seawater after 18 h was appropriate to match the trace and undetectable concentration levels of hydrocarbons recorded in field observations after this time.

### Behavioural Responses

The behavioural responses shown by the three species can be interpreted from the point of view of: direct toxicity effects of oil, the significance of these effects on survival to oil exposure, and finally interpreting the observations and conclusions originating from the field oil spills. In the latter case, meaningful correlations between this on-site controlled exposure study and the field spill cannot be made effectively until the benthic field data have been finally assembled and interpreted.

The description of behavioural changes in this study emphasizes $ET_{50}$ values and time to recovery to pre-exposure behaviour. It should be recognized that other behavioural changes occurred which may either not have affected 50% of the test population or else were sporadic in occurrence. These will be described only to round out the observations of behavioural effects.

*Mya truncata* was found to be a difficult species for an assessment of oil effects. Behavioural changes tended to be "noisy" insofar as they were quite variable and easily set off by disturbances other than oil. A clear dose-response could not be discerned using the above indices, but the higher concentrations were certainly more effective in inducing behavioural changes and in delaying recovery times. The trend of this bivalve to close ostia rapidly, and thereby arrest water flow, filtration and oil input, may be considered an advantage in surviving exposure to oil in seawater. The loss of responsiveness to mechanical stimuli may be considered as a narcotization response, although other physiological causes such as neural control override or muscle fatigue may have been contributory. Altogether, *M. truncata* was more resistant to oil than either *S. groenlandicus* or *S. droebachiensis*.

TABLE 11 HYDROCARBON CONCENTRATIONS IN TISSUES OF *MYA TRUNCATA* (MYA), *SERRIPES GROENLANDICUS* (SER), AND *STRONGYLOCENTROTUS DROEBACHIENSIS* (STR)

| | | | μg/g wet weight | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Exposure Condition[a] | Time | Species | ΣAB | N | $\Sigma C_1N$ | $\Sigma C_2N$ | $\Sigma C_3N$ | Total Aromatic | Total Oil |
| 0 | 6 h | MYA | 0.08 | 0.001 | 0.001 | 0.004 | 0.050 | 8.9 | 24 |
| | | SER | nd | nd | nd | nd | nd | nd | nd |
| | | STR | nd | nd | nd | nd | 0.093 | 17 | 44 |
| 0.5 | 6 h | MYA | nd | nd | nd | nd | 0.028 | 5.0 | 13 |
| | | SER | nd | nd | nd | 0.011 | 0.032 | 5.7 | 15 |
| | | STR | nd | nd | nd | nd | 0.116 | 21 | 55 |
| 5 | 6 h | MYA | 0.36 | 0.017 | 0.120 | 0.267 | 0.269 | 48 | 130 |
| | | SER | 0.64 | 0.024 | 0.194 | 0.457 | 0.455 | 81 | 217 |
| | | STR | nd | 0.005 | 0.063 | 0.059 | 0.137 | 25 | 65 |
| 50 | 6 h | MYA | 0.04 | 0.009 | 0.271 | 0.701 | 0.755 | 135 | 360 |
| | | SER | 0.12 | 0.01 | 0.33 | 0.91 | 0.76 | 136 | 360 |
| | | STR | 3.5 | 0.03 | 0.34 | 0.56 | 0.33 | 59 | 160 |
| 100 | 6 h | MYA | nd | nd | 0.10 | 0.61 | 0.50 | 89 | 240 |
| | | SER | nd | 0.1 | 0.21 | 0.60 | 0.37 | 66 | 180 |
| | | STR | nd | 0.01 | 0.22 | 0.12 | 0.06 | 11 | 29 |
| 250 | 6 h | STR | nd | nd | 0.03 | 0.03 | 0.04 | 7.7 | 21 |
| 250 (cv,lg) | 6 h | MYA | nd | nd | 0.23 | 0.53 | 0.38 | 67 | 180 |
| | | SER | nd | nd | 0.26 | 0.67 | 0.44 | 79 | 210 |
| | | STR | nd | nd | 0.01 | 0.09 | 0.04 | 7.0 | 19 |
| 250 (cv,sml) | 6 h | SER | nd | 0.01 | 0.12 | 0.22 | 0.12 | 22 | 59 |
| | | STR | nd | nd | 0.70 | 0.10 | 0.08 | 14 | 37 |
| 500 | 6 h | MYA | 0.05 | 0.01 | 0.54 | 1.9 | 1.5 | 270 | 710 |
| | | SER | 1.7 | 0.16 | 1.2 | 2.1 | 1.1 | 200 | 540 |
| | | STR | 0.5 | 0.05 | 0.30 | 0.20 | 0.06 | 11 | 31 |
| 0.5/5/0.2 | 18 h | MYA | nd | nd | nd | nd | 0.03 | 5.9 | 16 |
| | | SER | nd | nd | nd | 0.04 | 0.27 | 48 | 130 |
| | | STR | nd | nd | 0.04 | 0.06 | 0.04 | 7.9 | 21 |
| | 7 d | MYA | 0.01 | nd | 0.01 | 0.02 | 0.10 | 17 | 45 |
| | | SER | nd | nd | nd | 0.01 | 0.05 | 8.4 | 22 |
| | | STR | nd | nd | nd | 0.18 | 0.45 | 81 | 220 |
| 10/100/5 | 18 h | MYA | 0.03 | 0.36 | 0.42 | 1.6 | 1.3 | 240 | 630 |
| | | SER | nd | nd | 0.26 | 1.2 | 1.1 | 200 | 530 |
| | | STR | nd | nd | 0.11 | 0.48 | 0.32 | 56 | 150 |
| | 7 d | MYA | | | | | | | |
| | | SER | nd | nd | nd | 0.10 | 0.31 | 55 | 150 |
| | | STR | 0.08 | 0.01 | 0.24 | 0.88 | 1.1 | 190 | 510 |
| 10/100/5 (cv) | 18 h | MYA | 1.0 | 0.05 | 0.58 | 1.7 | 1.1 | 200 | 540 |
| | | SER | 0.39 | 0.05 | 0.05 | 0.18 | 0.20 | 37 | 99 |
| | | STR | 2.7 | 0.12 | 0.58 | 0.52 | 0.13 | 23 | 61 |
| | 7 d | MYA | 0.07 | nd | 0.32 | 0.31 | 0.72 | 130 | 340 |
| | | SER | nd | 0.10 | 0.20 | 0.10 | 0.36 | 65 | 170 |
| | | STR | nd | nd | 0.08 | 0.48 | 0.80 | 140 | 380 |

TABLE 11 HYDROCARBON CONCENTRATIONS IN TISSUES OF *MYA TRUNCATA* (MYA), *SERRIPES GROENLANDICUS* (SER), AND *STRONGYLOCENTROTUS DROEBACHIENSIS* (STR) (cont'd)

| | | | µg/g wet weight | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Exposure Condition[a] | Time | Species | ΣAB | N | $\Sigma C_1N$ | $\Sigma C_2N$ | $\Sigma C_3N$ | Total Aromatic | Total Oil |
| 10/100/5 | 18 h | MYA | 2.7 | 0.11 | 0.73 | 2.0 | 1.2 | 210 | 570 |
| | | SER | 0.03 | 0.01 | 0.43 | 1.9 | 1.8 | 320 | 860 |
| | | STR | 2.2 | 1.0 | 0.50 | 0.56 | 0.24 | 43 | 120 |
| | 7 d | MYA | ND | ND | ND | 0.01 | 0.10 | 18 | 47 |
| | | SER | ND | ND | ND | 0.01 | 0.07 | 12 | 33 |
| | | STR | 0.80 | 0.08 | 0.15 | 0.59 | 0.74 | 130 | 350 |

[a] In order: Exposure concentration (ppm); where indicated, cv specifies tanks were covered during exposure; animal size, large or small where indicated, otherwise medium size range.

nd = not detectable

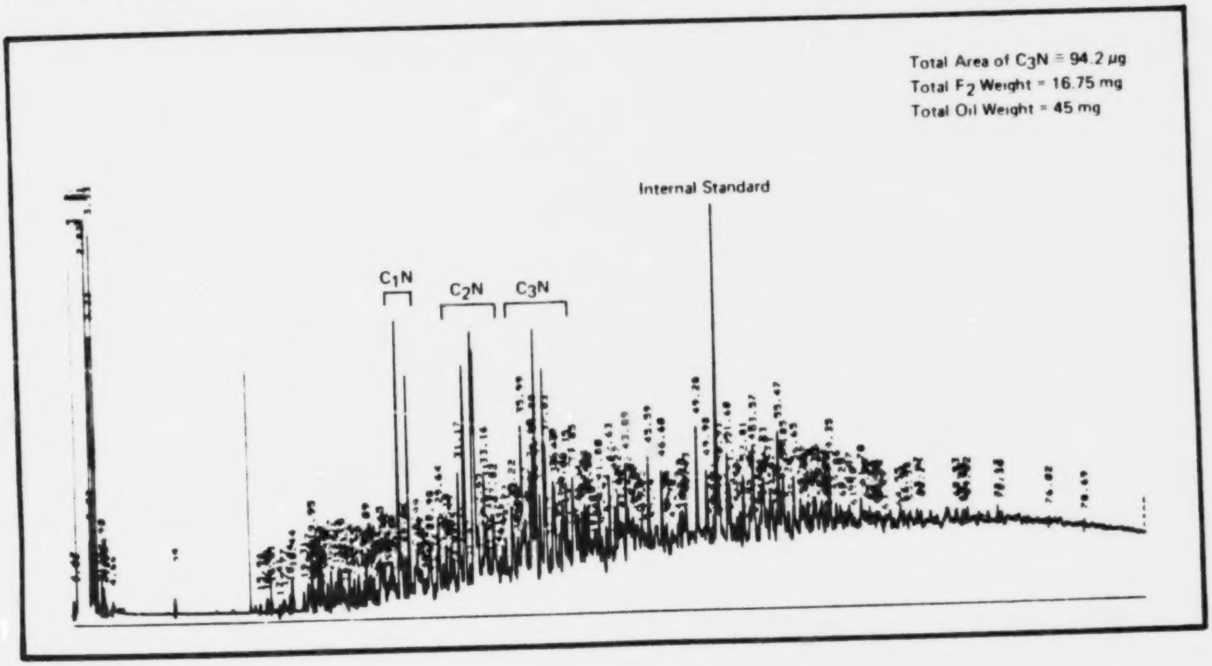

FIGURE 4 GC$^2$ TRACE OF AROMATIC FRACTION OF LAGO MEDIO CRUDE OIL

*Serripes groenlandicus* exhibited a more consistent and a wider behavioural response repertoire to oil exposure than did *M. truncata*. Both ostial closure and mantle/shell gape have relevance to the exposure of soft tissues to hydrocarbons. Closure of the ostia at even low concentrations of oil shut off filtration and limited the input of oil, explaining why the species showed few other responses at concentrations below 50 ppm. Conversely, rather than being an avoidance response, the mantle and shell gape which occurred both at higher concentrations and later in the experimental period are more likely to have been direct toxic effects. Both hydrocarbon narcosis and muscle fatigue are possible explanations.

The sporadic bursts of locomotion recorded at higher concentrations may be expected to expose sensitive tissues to oil. Exposure of soft tissues would also result from shell damage. The possibility of increased predation on the bivalve because of its emergence from the sediment, shell gaping, and shell damage has to be considered as a potential oil exposure effect on the benthic population. The decreased capacity to respond normally to tactile stimuli, as shown during exposure, suggests an early narcotizing effect. The latent recurrence of this negative response is more likely to have been of pathological origin.

Sequential dosing in *S. groenlandicus* pointed out that while the first low concentration phase was innocuous, similar to single exposures at the same concentration, a second exposure at a higher concentration elicited a markedly greater response than what would have been predicted from single exposures. This type of sequential exposure and corresponding response is similar to the situation reported for Bays 9 and 10 following the 1981 spill at Cape Hatt. Emergence and shell/mantle gaping were outstanding behaviour indices. The simplest explanation for the sensitivity of the species to sequential exposures may be that the animal has only a limited capacity to remain with shells closed. Once this time is exceeded (somewhat longer than 6 hours), the valves open and soft tissues become exposed to oil.

*Strongylocentrotus droebachiensis* served as a useful benthic species in which to observe the behavioural effects of dispersed crude oil. It was sensitive, showing responses even to 0.5 ppm of oil and demonstrating a fairly consistent dose response. A primary effect of oil exposure was debilitation of tube feet functions, causing loss of covering material and ability to adhere to substrate. The natural consequences of this may include an increased susceptibility to predation, displacement by currents, resulting in physical damage or removal from food source and habitat. This may be especially significant since this debilitating condition may last for several days even though the initial exposure may have been small and of short duration. The early responses of the tube feet, curling of aboral tube feet and loss of ability to respond to tactile stimulation, may result from the narcotizing effect of hydrocarbons in water. Distribution of hydrocarbons by the water vascular system of the urchin would generalize the response. Although interruption of water exchange was not verified, observations of the tube feet changes imply it was likely. Also, throughout the affected period, the peristomal membrane and the periproct regions displayed a sunken and flaccid appearance suggesting an impaired hydrostatic system.

A neuromuscular effect is implicated in the spine responses, again at least initially narcotic in nature. Spine drooping and spine rigidity alternated with each other and with a more normal radial but non-rigid arrangement. While spine drooping would increase the potential for damage and perhaps predation, spine rigidity would counter that effect. The response of assuming a more uniformly round, almost ball-like, appearance with rigid spines would, however, enhance the potential for physical displacement by currents.

Recovery of the spine system to respond to mechanical stimulation occurred sooner than did tube foot response, lending support to the suggestion that two different physiological systems were affected. Lethality occurred only during the 500 ppm single exposure test and during one of the Bay 9 simulating sequential tests. Recovery from the 500 ppm exposure was very limited, however; only two of the original 20 animals survived.

The responses to sequential dosing correlate well with divers' descriptions of the state of urchins in Bays 9 and 10 within a few days of the BIOS spill. Loss of adherence, narcotization, free movement in currents, and a decrease in the number of urchins in the spill area were all reported for that time period.

Tests of the effects of Corexit at 50 ppm, the amount used in 500 ppm oil dispersions, showed that all three species were responsive to the compound. The dispersant had a narcotizing effect on all three species, usually shortly after exposure. Recovery from all the noted responses for Corexit was rapid, however, and the overall effect of Corexit was much less than that of oil dispersions.

In all, the behavioural observations have shown that in these three major Arctic benthic species, the direct effects of short-term (6-h) exposure to dispersed oil are not likely to be fatal at 250 ppm or less. Behavioural changes may predispose these species, particularly *S. groenlandicus* and *S. droebachiensis*, to increased predation. Removal from habitat is another indirect effect, potentially most important to urchins.

### Tissue Hydrocarbons

The tissue hydrocarbon part of this study was little emphasized in this phase of the program, and was limited in terms of both sample size and analytical detail. It was evident, however, that all three species accumulated crude oil hydrocarbons.

The two bivalve species showed maximum levels by 6 h or 18 h, corresponding to the end points of exposure regimes. By 7 d, these levels generally had decreased, even to background concentrations in some instances. In urchins, however, a very different response was noted. Samples of tissues taken at 7 d showed an increased accumulation of hydrocarbons. The source of these is likely to have been from residues accumulated on the external body surface which were then absorbed even during the recovery period. This pattern may serve to explain the latent mortalities in the test populations. Further, an emphasis on volatile hydrocarbons such as the water-soluble alkyl benzenes in the 6 h samples may have been a major factor in the rapid early narcosis which was recorded for urchins.

The pattern of accumulation and release observed in these three species is the same as that observed in the field following the experimental spill (Boehm et al., 1982). The actual levels do not and cannot be expected to correlate since sampling times were not the same. The higher values recorded in this study at 6 h as compared to the first post-spill samples taken in the field may be attributed to differences in sampling times. During the tank study, sampling was carried out immediately after the oil exposure, whereas field study samples were taken 1 to 4 d after exposure.

A further phase of the study program is planned to define hydrocarbon uptake and clearance characteristics, and correlate them with the behavioural effects of dispersed oil exposure.

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# TOXICITY OF HYDROCARBONS AND CRUDE OILS

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## INTRODUCTION

There is an obvious need to determine the toxicity of oils and hydrocarbons to marine biota; a considerable volume of bioassay literature thus exists (NAS, 1975). In the study described here, we have sought relationships between hydrocarbon toxicity and physical chemical properties. Such structure-activity relationships are invaluable because they generate the potential to predict (at low cost) instead of measuring (at high cost) the toxicity of hydrocarbons.

A frequent experimental difficulty in toxicity studies is the presence of vapour losses from the hydrocarbon solution during the bioassay, resulting in organism exposure to decreasing concentrations of toxicant. This is particularly important when the toxicant has a high air-water partition coefficient or Henry's Law Constant, which is essentially the ratio of vapour pressure to solubility. Although many hydrocarbons have very low vapour pressures, they may also have very low solubilities, and thus the ratio remains large (Mackay and Shiu, 1981). For this reason, truly closed or air-tight systems are preferred for such toxicants (Rogerson et al., 1983; Bobra et al., 1983a). Such systems appear to give more reproducible exposure conditions. In the latter study, Bobra et al. (1983) described a method of exposing the water flea, *Daphnia magna*, to hydrocarbon solutions in the absence of an air space.

Although *Daphnia* is not a marine organism, it is frequently used for aquatic toxicity bioassays (Bobra et al., 1983a; Bringman and Kuehn, 1982; Buikema et al., 1979; Leblanc, 1980; Lee, 1976). Test results have contributed to the data base which is necessary to perform aquatic safety assessments for chemicals and to establish water quality criteria and standards (Buikema et al., 1979; APHA, 1976; ASTM, 1980; Kimerle and Duthie, 1978; Maki and Duthie, 1978; EPA, 1975). Attempts have also been made to relate the toxicity of *Daphnia* to other organisms (Kenaga, 1978).

A second difficulty in assessing the toxicity of oil mixtures is that there is rarely complete or even detailed information about the nature and concentration of all the individual hydrocarbons present. Crude oils are particularly complex and variable mixtures. An important practical consideration is that when a crude oil weathers in the environment, its composition changes and its toxicity presumably also changes. It is often suggested that certain classes of hydrocarbons, such as benzenes or naphthalenes, are the primary toxicants; their removal by evaporation processes may thus cause a decrease in toxicity. Also, it is not clear how information about individual compound toxicities should be combined when predicting the toxicity of mixtures.

This report describes a research program at the University of Toronto in which we have measured toxicities and interpreted the results thermodynamically (Bobra et al., 1983a, b).

## MATERIALS AND METHODS

Saturated aqueous solutions of solid hydrocarbons (see Table 1) with a density greater than that of water were prepared by adding an excess quantity of the compound to double-distilled water in 250 mL glass flasks with glass stoppers. The solutions were stirred vigorously with a Teflon-coated magnetic bar for 24 hours. Saturated aqueous solutions of liquid hydrocarbons and fresh and weathered crude oils (see Tables 1 and 2) which have a density less than water were prepared by adding an excess quantity of the compound to double-distilled water in 250 mL cylindrical separatory funnels. The mixtures were then shaken gently on a wrist action shaker for 12 hours. All the solutions were allowed to settle at room temperature for at least 48 hours before removing a water sample for the bioassay.

Weathered samples of crude oils were prepared by evaporating the oil in a pan in a wind tunnel at 20°C or by using an air stripping apparatus consisting of a glass vessel into which air was bubbled. The samples were continuously weighed on a top-loading balance.

The concentrations of pure hydrocarbons in the bioassays were calculated from available literature solubility data of compounds (Table 1) and from the extent of dilution. The concentrations of the aqueous phases in equilibrium with the oils (i.e., the "water-soluble fraction") were determined using a Hewlett Packard GC Model 5840A equipped with a flame ionization detector and a 7675A Purge and Trap sampler. The column was a 50 m x 0.5 mm I.D. glass WCOT column coated with SE 30. The GC oven was temperature programmed from 50°C to 220°C at a rate of 5°/min.

*Daphnia magna* obtained from laboratory cultures of parthenogenetic females were used for all bioassays. The stock cultures were fed trout chow and algae, and kept in distilled water with a pH of approximately 6.5. *Daphnia* of similar size (1.5 mm long, 4 to 6 days old) were selected visually from the stock cultures for the bioassays. The *Daphnia* bioassays were performed in 24 mL glass vials with Teflon-lined screw-on caps, 10 animals per vial. The vials had no air spaces and were not aerated, nor were the animals fed during the bioassay. *Daphnia* mortalities were observed after 48 hours. Mortality data from each of the toxicity tests were used to estimate median lethal concentrations ($LC_{50}$).

TABLE 1 THE ACUTE TOXICITY OF HYDROCARBONS TO *DAPHNIA MAGNA* IN A CLOSED SYSTEM

| Compound | Solubility[c] (mmol/m$^3$) | $LC_{50}$ (mmol/m$^3$) | n[e] | 95% Confidence Interval | $LC_{50}CL$ | Predicted[d] $LC_{50}$ (mmol/m$^3$) |
|---|---|---|---|---|---|---|
| ALKANES | | | | | | |
| pentane | 534[a] | 135 | 5 | 111-164 | 0.25 | 59 |
| hexane | 110 | 45 | 5 | 30-66 | 0.41 | 22 |
| octane | 5.8 | 3.3 | 5 | 2.7-4.0 | 0.57 | 3.3 |
| decane | 0.35 | 0.2 | 5 | 0.1-0.3 | 0.57 | 0.6 |
| CYCLOALKANES | | | | | | |
| cyclopentane | 2 224 | 150 | 5 | 85-268 | 0.07 | 140 |
| cyclohexane | 654 | 45 | 5 | 34-60 | 0.07 | 63 |
| methyl cyclohexane | 143 | 15 | 5 | 9-25 | 0.11 | 24 |
| MONOAROMATICS | | | | | | |
| benzene | 22 788 | 400 | 10 | 285-554 | 0.02 | 538 |
| toluene | 5 590 | 125 | 5 | 58-271 | 0.02 | 217 |
| ethyl benzene | 1 431 | 20 | 5 | 5-78 | 0.01 | 91 |
| o-xylene | 1 742 | 80 | 6 | 44-147 | 0.05 | 103 |
| m-xylene | 1 525 | 90 | 6 | 58-138 | 0.06 | 95 |
| p-xylene | 1 648 | 30 | 6 | 11-83 | 0.02 | 99 |
| 1,2,4-trimethyl benzene | 474 | 30 | 5 | 13-69 | 0.06 | 45 |
| 1,3,5-trimethyl benzene | 807 | 50 | 5 | 22-110 | 0.06 | 62 |
| cumene | 416 | 5 | 6 | 1-30 | 0.01 | 42 |
| 1,2,4,5-tetramethyl benzene | 26 | 3.5 | 5 | 1-11 | 0.14 | 7.6 |
| POLYNUCLEAR AROMATICS | | | | | | |
| naphthalene | 944[a]<br>268[b] | 130 | 9 | 91-181 | 0.14 | 66 |
| 1-methyl naphthalene | 200 | 10 | 7 | 3-40 | 0.05 | 25 |
| 2-methyl naphthalene | 222[a]<br>179[b] | 13 | 7 | 5-35 | 0.06 | 27 |
| biphenyl | 138[a]<br>49[b] | 20 | 5 | 1-56 | 0.15 | 19 |
| phenanthrene | 37[a]<br>6.6[b] | 6.5 | 5 | 3-12.5 | 0.18 | 8.4 |
| anthracene | 33[a]<br>0.4[b] | 17 | 5 | 1->33 | 0.52 | 7.8 |
| 9-methyl anthracene | 4.6[a]<br>1.3[b] | 2.3 | 6 | 0.8->4.6 | 0.50 | 2.3 |
| pyrene | 14[a]<br>0.7[b] | 9 | 5 | 1->14 | 0.64 | 4.4 |

[a] Estimated subcooled liquid solubility, using fugacity ratio.

[b] Actual solid solubility.

[c] From Hutchinson et al. (1980).

[d] Predicted $LC_{50}$ values were calculated using the correlation log $LC_{50} = 0.597 \log C_t - 0.317$ taken from Figure 1. Correlation coefficient for predicted versus experimental $LC_{50}$ values is 0.929.

[e] Number of test concentrations.

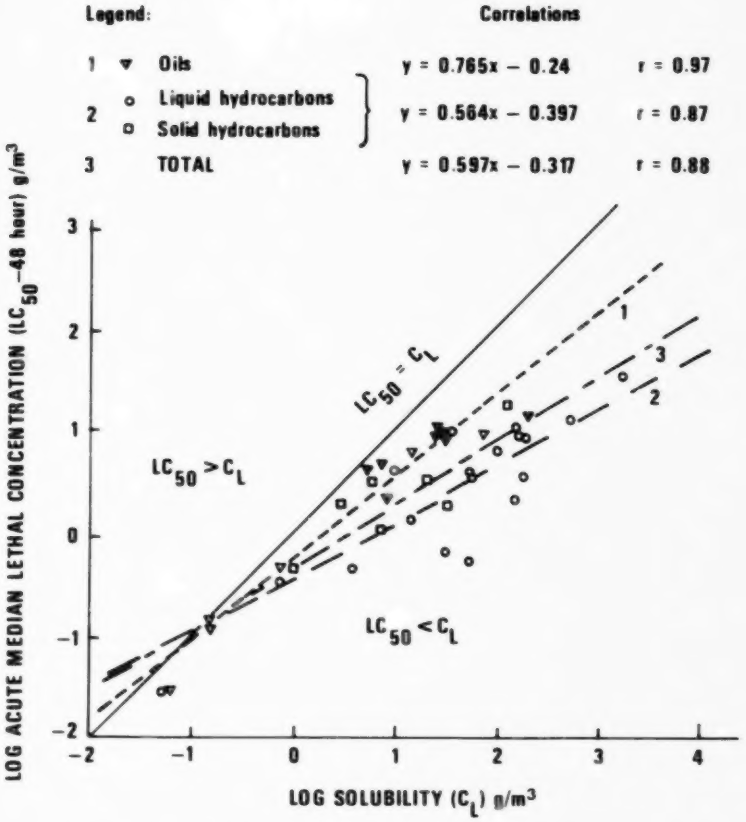

FIGURE 1 ACUTE MEDIAN LETHAL CONCENTRATIONS ($LC_{50}$) OF HYDROCARBONS AND FRESH AND WEATHERED OILS TO *DAPHNIA MAGNA* IN A CLOSED SYSTEM VERSUS SOLUBILITIES

## RESULTS AND DISCUSSION

A summary of the acute toxicity results of the water-soluble fraction of the various crude oils and pure hydrocarbons to *Daphnia magna* in a closed system is presented in Tables 1 and 3, and in Figure 1. The most soluble compounds of the various fresh and weathered crude oils in double-distilled water were identified and are tabulated in Table 2. In fresh crude oils, the most soluble compounds are the monoaromatics. The acute toxicities of the pur hydrocarbons varied from 0.2 to 400 mg/L while those of the fresh oil solutions ranged from 7.4 to 13.5 mg/L; the total solubilities of the oils extended over a wide range, from 25.5 to 203 mg/L. The toxicity results for weathered oils are more varied.

In light of these results, it is interesting to examine the issue of how crude oil weathering influences toxicity. Figure 2 is a plot of the aqueous solubilities and $LC_{50}$s of Norman Wells crude oil versus the extent of weathering. Weathering a crude oil causes a marked reduction in solubility and a reduction in $LC_{50}$, but the fraction of the solubility necessary to produce lethality increases until it eventually is believed to exceed 100%, i.e., it becomes impossible to form a lethal aqueous solution. Thus, weathering produces aqueous solutions which are more toxic, in the sense of having lower $LC_{50}$s; however, the saturated solutions of weathered crude oils are less toxic, as are the equi-diluted saturated solutions.

TABLE 2 AQUEOUS SOLUBILITY (g/m$^3$) OF VARIOUS CRUDE OILS

| Crude Oil | Degree of Weathering (% evaporated) | Benzene | Toluene | Ethyl Benzene, Xylenes and Cumene | Residue | Total |
|---|---|---|---|---|---|---|
| Norman Wells[a] | 0 | 12.0 | 7.6 | 2.3 | 10.3 | 32.3 |
| | 6 | 8.8 | 7.8 | 3.9 | 6.5 | 27.0 |
| | 12 | 5.3 | 5.5 | 2.3 | 1.5 | 14.6 |
| | 20.4 | 1.8 | 2.3 | 1.8 | 1.4 | 7.3 |
| | 36.7 | 0.13 | 0.033 | 0.012 | 0.5 | 0.68 |
| | 43.2 | 0.026 | 0.037 | 0.024 | 0.053 | 0.14 |
| Prudhoe Bay[a] | 0 | 11.1 | 8.3 | 3.7 | 6.2 | 29.3 |
| | 9.8 | 0.41 | 1.6 | 1.9 | 1.0 | 4.91 |
| | 18.2 | 0.020 | 0.025 | 0.024 | 0.084 | 0.153 |
| | 24.4 | 0.040 | 0.051 | 0.0021 | 0.009 | 0.102 |
| Lago Medio[b] | 0 | 7.12 | 6.58 | 3.51 | 8.3 | 25.5 |
| | 22.3 | 0.013 | 0.012 | 0.006 | 0.58 | 0.61 |
| Murban | 0 | 7.88 | 7.77 | 4.53 | 8.44 | 28.62 |
| Natural Gas Condensate | 0 | 22.08 | 32.34 | 13.36 | 6.97 | 74.65 |
| | 42 | 0.002 | 0.024 | 2.76 | 5.23 | 8.02 |
| | 71 | - | - | - | 0.057 | 0.057 |
| Synthetic Oil Mixture[b] | 0 | 114 | 61.1 | 19.4 | 8.9 | 203.4 |

[a] Mackay and Shiu (1975).

[b] Chau (1983).

TABLE 3 THE ACUTE TOXICITY OF THE WATER-SOLUBLE FRACTIONS OF VARIOUS FRESH AND WEATHERED CRUDE OILS TO *DAPHNIA MAGNA* IN A CLOSED SYSTEM

| Crude Oil | Degree of Weathering (% evaporated) | Solubility $C_L$ (g/m$^3$) | $LC_{50}$[a] (g/m$^3$) | 95% Confidence Intervals | $LC_{50}/C_L$ | Predicted[b] $LC_{50}$ (g/m$^3$) | Predicted[c] $LC_{50}$ (g/m$^3$) |
|---|---|---|---|---|---|---|---|
| Norman Wells | 0 | 32.3 | 9.0 | 4-20 | 0.28 | 3.8 | 10.8 |
| | 6 | 27 | 10.8 | 9-13 | 0.40 | 3.4 | 7.7 |
| | 12 | 14.6 | 6.0 | 4.5-8 | 0.40 | 2.4 | 5.6 |
| | 20.4 | 7.3 | 4.4 | 2->7.3 | 0.60 | 1.6 | 3.5 |
| | 36.7 | 0.68 | 0.49 | 0.2->0.68 | 0.72 | 0.38 | 0.5 |
| | 43.2 | 0.14 | 0.12 | 0.06->0.14 | 0.85 | 0.15 | 0.1 |
| Prudhoe Bay | 0 | 29.25 | 9.4 | 5-15.6 | 0.32 | 3.6 | 8.4 |
| | 9.8 | 4.89 | 3.9 | 3-4.9 | 0.80 | 1.2 | 2.4 |
| | 18.2 | 0.15 | 0.15 | - | 1.0 | 0.16 | 0.1 |
| | 24.4 | 0.10 | >0.1 | - | >1.0 | 0.12 | - |
| Lago Medio | 0 | 25.5 | 7.7 | 4-14.8 | 0.30 | 3.3 | 8.0 |
| | 22.3 | 0.6 | >0.6 | - | >1.00 | 0.36 | - |
| Murban | 0 | 28.6 | 7.4 | 3.3-16.6 | 0.26 | 3.6 | 7.9 |
| Natural Gas Condensate | 0 | 74.7 | 9 | 4-29.6 | 0.12 | 6.3 | 8.3 |
| | 42 | 8.0 | 2 | 0.6-5.6 | 0.25 | 2.1 | 3.6 |
| | 71 | 0.06 | 0.03 | 0.01->0.06 | 0.50 | 0.09 | 0.046 |
| Synthetic Oil Mixture | 0 | 203.4 | 13.5 | 4.1-44.8 | 0.07 | 11.5 | 12.5 |

[a] Experimental concentration lethal to 50% of the population.

[b] Predicted concentration lethal to 50% of the population using the correlation $\log LC_{50} = 0.597 \log C_L - 0.317$. Correlation coefficient for predicted versus experimental $LC_{50}$ values is 0.857.

[c] Predicted $LC_{50}$ values were calculated using the Finney's multiple toxicity equation. Correlation coefficient for predicted versus experimental $LC_{50}$ values is 0.96.

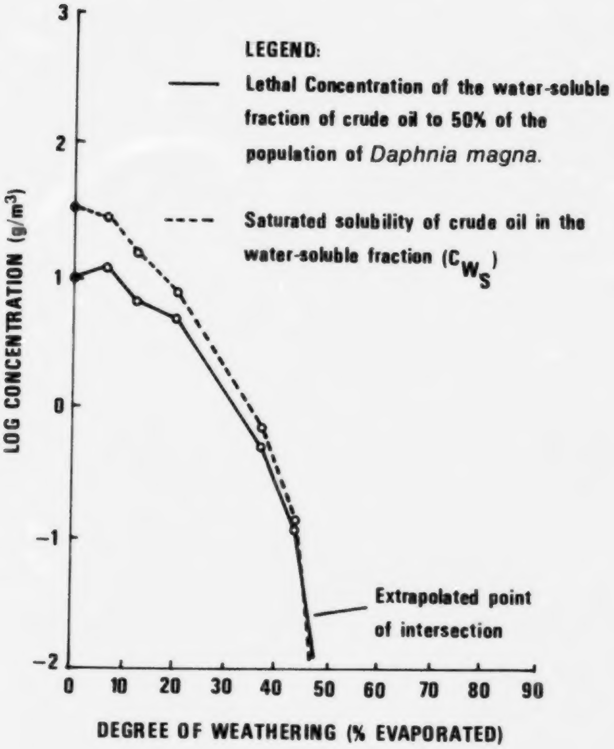

FIGURE 2 AQUEOUS SOLUBILITIES AND $LC_{50}$s OF NORMAN WELLS CRUDE OIL VERSUS THE EXTENT OF WEATHERING

For thermodynamic reasons not discussed here, we believe that the appropriate correlation for solid hydrocarbons is not the actual solubility but the solubility which it would have if it was a liquid. This can be estimated as:

$$C_L = C_S \exp(-6.79(1 - T_M/T))$$

where $C_L$ is the estimated subcooled liquid solubility

$C_S$ is the actual solid solubility

$T_M$ is melting point (K)

T is the system temperature (K) (Rogerson et al., 1983; Bobra et al., 1983a)

Figure 1 shows the $LC_{50}$ to correlate well with $C_L$, as was shown in hydrocarbon studies using algae (Hutchinson et al., 1980) and ciliated protozoa (Rogerson et al., 1983). Thus, one approach for correlating the toxicity of aqueous solutions of pure hydrocarbons and fresh and weathered oils to *Daphnia* is to measure the aqueous solubility ($C_L$), then read off an estimated $LC_{50}$ value from Figure 1 or calculate the $LC_{50}$ from the equation relating $LC_{50}$ to the solubility ($C_L$) (Tables 1 and 3):

$$\log LC_{50} = 0.597 \log C_L - 0.317$$

$C_L$ can be predicted from the molecular weight or surface area; the $LC_{50}$ can thus potentially be predicted from molecular structure.

It is interesting to note that in Figure 1, after the regression line crosses the 45° diagonal (at which point $LC_{50}$ equals $C_L$), the $LC_{50}$ values are larger than the $C_L$ values. Thus, it is impossible to make an aqueous solution which is toxic to 50% of the population. This applies to very weathered oils and to high-molecular-weight solid polynuclear aromatics which have low $C_L$ values and even lower $C_S$ values.

Another method of correlating the toxicity of fresh and weathered crude oils has been proposed in which the toxicities of the dominant dissolved components are added. We have postulated that there are four dominant groups in the aqueous solutions of the various oils:

1 = benzene

2 = toluene

3 = ethyl benzene, xylenes (*o*-, *p*-, *m*-) and cumene

4 = "residue"

The $LC_{50}/C_L$ values for benzene, toluene, and ethyl benzene, xylenes and cumene were taken from the hydrocarbon bioassays. The ratio $LC_{50}/C_L$ for residue was assumed to be 0.8. As indicated in Table 2, the $LC_{50}$ values were predicated for all the oils by using these values in an equation which can be shown to reduce to a multiple toxicity equation (Finney, 1971), namely:

$$1/LC_{50} \text{ of mixture} = \sum_i (f_i/LC_{50_i})$$

where $f_i$ is the fraction of substance in the mixture.

The correlation coefficient between the predicted versus experimental values is 0.96. In this additive toxicity model, individual $LC_{50}$ values are assigned to the major dissolved hydrocarbons and to a residue.

We believe that this work demonstrates that toxicity is controlled by the extent of partitioning of hydrocarbon into the organism. This is in turn controlled by the factor by which the concentration is less than the saturation value, not the absolute concentration. An implication is that equi-toxic effects occur at approximately the same hydrocarbon concentration in the organism, with the hydrocarbon's chemical structure playing only a secondary role. It would be fruitful to examine other hydrocarbons, oils, chlorinated hydrocarbons and organisms to explore if similar relationships apply. If they do, the entire issue of hydrocarbon toxicology will become much more predictable.

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# SESSION III SHORELINE PROTECTION AND CLEANUP

## THE BIOS SHORELINE EXPERIMENTS: RESULTS FROM 1980-1982 FIELD STUDIES

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### INTRODUCTION

Field studies have been conducted over a period of 3 years in the vicinity of Cape Hatt, on Baffin Island, to assess selected shoreline cleanup countermeasures. It is now possible to reach some general conclusions regarding the relative efficiency and effectiveness of the countermeasures that were tested experimentally, and to relate these results to the fate of oil in the shore zone in terms of the expected residence time or persistence of stranded oil. The field program has produced an extensive data set that is available in the BIOS Working Report Series, available from the BIOS Project Office, Environment Canada, Edmonton. The objective of this paper is to present briefly some of the interesting results that have emerged to date. No attempt has been made here to document the experimental results in detail, but simply to present an outline of the project status.

### OIL LOADINGS

Plots of aged crude and water-in-aged crude oil emulsion were laid down at various locations using a gravity and pump distribution system. Table 1 shows the mean values and the range of values of total hydrocarbon samples that were collected from the different plots immediately after distribution of the oil; the plot locations are shown on Figure 1. The data indicate that oil loadings were higher, in most cases, on the crude plots than on the emulsion plots. A particularly significant point is that the oil loading on the crude oil plots is in the same general range as the total hydrocarbon samples that were collected from Bay 11, where a large volume of crude oil was allowed to wash ashore on the water surface. This indicates that the experimental plots were reasonable replicates of real-world contaminated beach areas.

TABLE 1 POST-OILING SURFACE t-h SAMPLE ANALYSIS RESULTS

| | Mean | | Range |
|---|---|---|---|
| (1) CRUDE PLOTS | | | |
| HC | 36,500 | | 11,600 - 77,400 |
| Crude Oil Point (all plots) | 17,825 | | 4,310 - 25,000 |
| LC | 17,133 | | 6,700 - 36,000 |
| Bay 106 (all plots) | 9,400 | | 4,090 - 15,300 |
| Bay 11 | 10,612 | | 470 - 18,000 |
| $\bar{x}$ | 16,174 | mg/kg | 470 - 77,400 |
| (2) EMULSION PLOTS | | | |
| HE | 13,667 | | 1,900 - 23,200 |
| Crude Oil Point | 13,843 | | 7,370 - 24,000 |
| LE | 3,167 | | 1,300 - 4,500 |
| Bay 106 | 7,130 | | 4,850 - 8,800 |
| $\bar{x}$ | 9,497 | mg/kg | 1,300 - 24,000 |

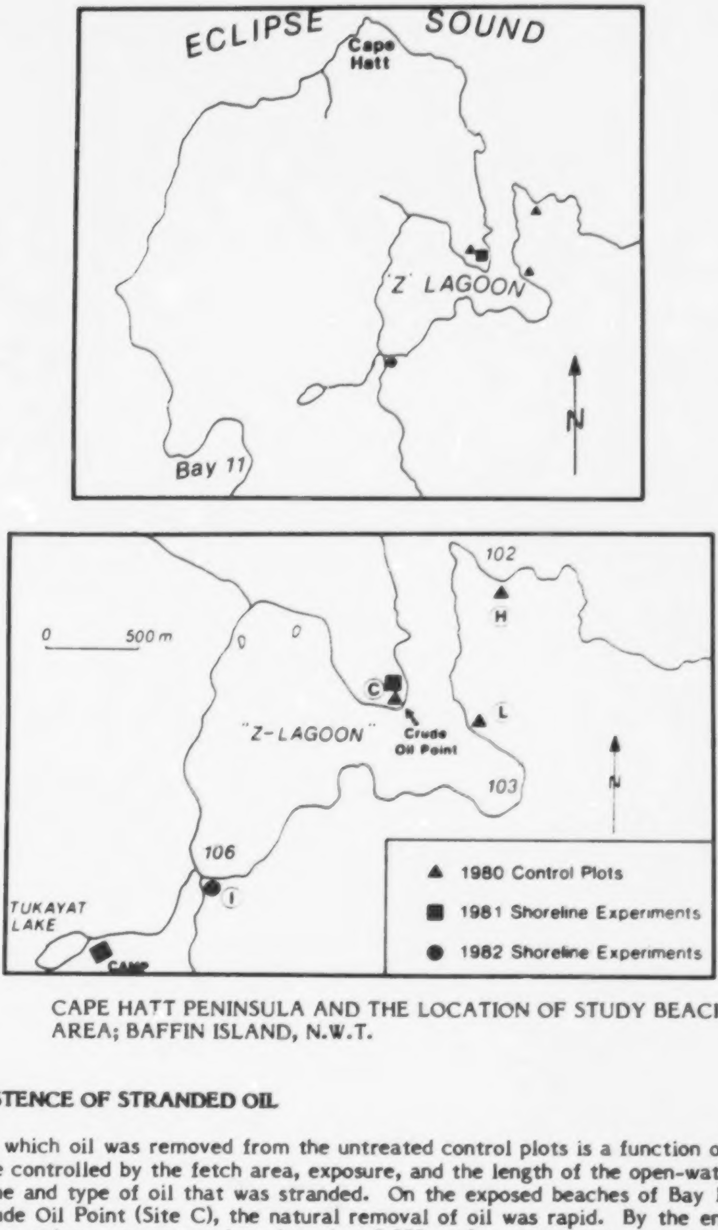

FIGURE 1 CAPE HATT PENINSULA AND THE LOCATION OF STUDY BEACHES IN THE "Z-LAGOON" AREA; BAFFIN ISLAND, N.W.T.

## THE PERSISTENCE OF STRANDED OIL

The rate at which oil was removed from the untreated control plots is a function of a) wave-energy levels at the shoreline, which are controlled by the fetch area, exposure, and the length of the open-water season; b) the sediment types; and c) the volume and type of oil that was stranded. On the exposed beaches of Bay 102 (Site H) and the semi-exposed beaches of Crude Oil Point (Site C), the natural removal of oil was rapid. By the end of the first open-water season, total hydrocarbon values were everywhere less than 3,000 mg/kg; and on only one plot (CC) did the remaining oil exceed 10% of the original loading (Tables 2 and 3). On the sheltered plots in "Z-Lagoon" (Site L), considerable amounts of oil remained on the crude oil plot even after 3 years (Table 2).

The results clearly indicate that natural cleaning was a function of wave activity and the redistribution of intertidal sediments and oil on the exposed beach in Bay 102. Natural cleaning occurred over less than two open-water seasons (approximately 100 days). The semi-exposed beaches of Crude Oil Point have a lower wave-energy environment than does Bay 102 due to their location within the inlet entrance; however, after two open-water seasons, these plots retained less than 0.05% of oil-in-sediment by weight (500 mg/kg) (Table 2). Within "Z-Lagoon" itself, considerable amounts of oil remained on the crude oil plot in Bay 103 even after 3 years. The Bay 103 crude oil plot (LC) is apparently very similar to the situation that occurred in Bay 11, where oil was stranded on the beach from the water surface. In Bay 11, the mean value of all of the total hydrocarbon samples was reduced from 6,500 mg/kg in the first year to 4,375 mg/kg at the end of the second survey (Table 4). Further sampling in Bay 11 is planned for 1983 and will provide data over a 3-year period for this site. Subsequent sampling may be possible in future years (i.e., 1985 or 1986) to provide information on the long-term persistence of stranded oil in this location.

TABLE 2 TOTAL HYDROCARBON VALUES (mg/kg, weight of oil in sediment) FROM INTERTIDAL CONTROL PLOTS

(a)

| Sample | INITIAL 1980 | FALL 1980 | JULY 1981 | FALL 1981 | AUG 1982 | SEPT 1982 |
|---|---|---|---|---|---|---|
| HC Surface | 36 000 | 1 200 | 1 890 | 0 | 0 | 0 |
| Subsurface | 12 000 | 20 | 1 730 | 0 | 0 | 0 |
| HE Surface | 13 700 | 20 | 1 210 | 0 | 0 | 0 |
| Subsurface | 10 500 | 6 | 260 | 0 | 0 | 0 |
| LC Surface | 17 100 | 6 400 | 4 720 | 1 600 | 3 150 | 4 640 |
| Subsurface | 15 500 | 13 900 | 5 000 | 4 900 | 9 520 | 5 170 |
| LE Surface | 3 400 | 130 | 140 | 150 | 70 | 10 |
| Subsurface | 1 400 | 80 | 70 | 160 | 0 | 0 |

(b)

| Sample | INITIAL 1981 | AFTER 8 DAYS | FALL 1981 (40 DAYS) | AUG 1982 | SEPT 1982 |
|---|---|---|---|---|---|
| CC Surface | 21 000 | 17 000 | 3 110 | 300 | 80 |
| Subsurface | 3 020 | 1 500 | 150 | 3 380 | 220 |
| CE Surface | 12 000 | 21 700 | 930 | 90 | 500 |
| Subsurface | 1 060 | 380 | 110 | 390 | 300 |

c)

| Sample | INITIAL 1982 | FALL 1982 |
|---|---|---|
| IC Surface | 15 300 | 2 130 |
| Subsurface | - | - |
| IE Surface | 8 800 | 830 |
| Subsurface | - | - |

NOTE: (i) The prefixes H, C, L, and I refer to the beach sites located on Figure 1.

(ii) The suffixes C and E refer to aged crude and emulsified oils respectively.

TABLE 3 REDUCTION (%) OF ORIGINAL STRANDED OIL

| Sample | First Open-Water Season | Second Open-Water Season | Third Open-Water Season |
|---|---|---|---|
| HC Surface | 97 | 100 | 100 |
| Subsurface | 99.8 | 100 | 100 |
| CC Surface | 85 | 99.6 | - |
| Subsurface | 95 | 93 | - |
| LC Surface | 62.5 | 91 | 72 |
| Subsurface | 10.3 | 68 | 45 |
| HE Surface | 99.8 | 100 | 100 |
| Subsurface | 99.9 | 100 | 100 |
| CE Surface | 92 | 96 | - |
| Subsurface | 90 | 72 | - |
| LE Surface | 96 | 96 | 99 |
| Subsurface | 95 | 89 | 100 |

NOTE: Last samples were collected approximately 4 weeks prior to the end of each open-water season.

TABLE 4 BAY 11 SURFACE OIL COVER CHARACTERISTICS

| | Intertidal Oiled Area ($m^2$) | Mean Oil Covering (%) | Mean Hydrocarbon Content (mg/kg) | |
|---|---|---|---|---|
| | | | Surface | Subsurface |
| August 1981 Survey | 9,560 | 58.5 | 6,500 | 234 |
| August 1982 Survey | 11,320 | 36.9 | 4,375 | 1,026 |
| 1981 to 1982 Change | +1,760 | -21.6 | | |

The types of sediments that exist in the intertidal zone control, to a large degree, the initial oil loading and the penetration of oil into the subsurface sediments. Data from the 1982 experiments carried out in Bay 106 (Site I) show that no penetration of the oil could be detected at the 10 cm depth (Table 2c). This is in contrast to the sand and sandy-gravel beaches of the other "Z-Lagoon" locations where subsurface total hydrocarbon values were commonly in excess of 1,000 mg/kg and occasionally were greater than 10,000 mg/kg (Tables 2a and 2b).

It is not possible in this brief summary to present all of the analytical results, but biogeochemical data show that the evaporative weathering processes associated with the degradation of stranded oil were most significant during the first two open-water seasons. Where data are available over a 3-year period, the analytical results indicate little change between the end of the second open-water season and the third open-water season. By contrast, the alkane/isoprenoid ratios show little activity associated with biodegradation during the first open-water season but indicate a significant reduction in the ratios, and therefore significant biological activity, on the intertidal plots between the end of the first open-water season and the end of the second open-water season. One set of data, from the Crude Oil Point plots, that illustrates these trends is given in Table 5 (Owens et al., 1983b).

TABLE 5 SUMMARY OF MEANS OF RESULTS FROM ALL 1981 COUNTERMEASURES AND CONTROL PLOTS AT CRUDE OIL POINT

| | 1981 | | | | 1982 | |
|---|---|---|---|---|---|---|
| | Pre-Test | Post-Test | +8 Days | +40/41 Days | Aug. 8-Aug. 10 | Aug. 29-Sept. 02 |
| SHWR | 2.3[a] | 2.7 | 2.1 | 1.8 | 1.5 | 1.1 |
| ALK/ISO | 2.5[a] | 2.6 | 3.0 | 2.3 | 2.4 | 1.6 |

[a] Aged crude oil.

## COUNTERMEASURES EXPERIMENTS

The results of dispersant tests carried out during 1981 are described in detail elsewhere (Owens et al., 1982, 1983a). The data indicate that application of dispersants on the Crude Oil Point plots resulted in a significant reduction of the total hydrocarbon values during the initial part of the sampling period. By the end of the first open-water season, however, the total hydrocarbon values on the control plots were of the same order of magnitude as those from the plots that had been treated with dispersant. Therefore, it was concluded that the technique might be of value in situations where rapid cleaning of a shoreline was deemed to be necessary. Further data collected during 1982 indicate that, although all of the Crude Oil Point plots were basically clean (<500 mg/kg), less oil remained on the plots where the dispersant was used than on the plots where mixing was applied or on the control plots.

Dispersants were applied during 1983 to intertidal plots in Bay 106, the very sheltered location at the head of "Z-Lagoon" (Figure 1). Results from these tests indicate that the dispersants were not effective in reducing total hydrocarbon contents on the plots. In this very low wave-energy environment, insufficient mixing energy was available to remove the oil/dispersant from the beaches. Comparing the two sites of Crude Oil Point and Bay 106, dispersant efficiency decreased with a decrease in wave-energy levels. Although the dispersant may have been effective from the chemical viewpoint, the fact that waves were unable to remove the oil/dispersant meant that, for practical purposes, the dispersant could not be considered an effective cleaning method without additional inputs of either natural or man-made energy.

One of the intertidal plots in Bay 106 was treated with a low-pressure hose without a dispersant to determine if this type of flushing would be effective in a low wave-energy environment. The results from this test indicate clearly that the total hydrocarbon values were not reduced by this type of flushing action. The data indicate that, by the time of the last sample set of 1983, there was little difference between the use of low-pressure flushing with a dispersant added and the low-pressure flushing that used seawater only.

A series of mixing experiments were conducted in the intertidal zone at Crude Oil Point and on the backshore in Bay 106. The experiments at Crude Oil Point show that the mixing action delayed degradation and also pushed oil deeper into the beach sediments. By the second open-water season, the intertidal mixed plots were relatively clean, largely as a result of wave action that redistributed contaminated sediments; however, total hydrocarbon values were slightly higher than on the plots where dispersants were used at this location. The values on the mixed plots were of the same order of magnitude, but slightly higher, than those from the intertidal control plots at Crude Oil Point. On the backshore plots, mixing proved to be effective in reducing total hydrocarbon values of the surface sediments. The data indicate that this reduction was in excess of 50% over much of the plots, when compared to adjacent control plots (Table 6). In this instance, oil was again pushed deeper into the sediments, so that subsurface total hydrocarbon values increased significantly when compared to the control plots. If the objective of the exercise is to reduce surface oil volumes alone, however, then the technique may have some value in backshore environments where oil has been stranded above the limit of normal wave activity: for example, during periods of high wave activity or storm surges.

TABLE 6 BAY 106 TOTAL HYDROCARBON RESULTS: BACKSHORE SURFACE SAMPLES (mg/kg) (from Owens et al., 1983b)

| | IMC | | IME | | |
|---|---|---|---|---|---|
| | control | mixed | mixed | control | |
| **backbeach** | 23,800 | 24,200 | 42,200 | 18,400 | **PRE-TEST**<br>**14 August** |
| **berm** | 106,000 | 56,500 | 17,100 | 12,400 | |
| **backbeach** | 20,600 | 12,700 | 12,300 | 34,500 | **POST TEST**<br>**15 August**<br>**(day 0)** |
| **berm** | 66,900 | 23,200 | 9,270 | 7,730 | |
| **backbeach** | 38,200 | 14,500 | 24,800 | 40,000 | **POST TEST**<br>**22 August**<br>**(+7 days)** |
| **berm** | 88,600 | 18,700 | 13,800 | 8,640 | |
| **backbeach** | 32,600 | 18,200 | 16,700 | 65,200 | **POST TEST**<br>**15 September**<br>**(+31 days)** |
| **berm** | 57,100 | 31,100 | 8,510 | 5,350 | |

Other countermeasures tests were conducted during 1981 to assess the value of solidifying agents and of burning. A gelling agent was used on plots at Crude Oil Point in an attempt to solidify the stranded oil. These tests were effective and the solidified oil was still present in the intertidal zone after two open-water seasons. The solidifier bonded the sediments and the wave action at this semi-exposed site was not sufficient to break up the solidifier/oil/sediment mixture. Attempts to burn oil on intertidal plots during 1981 were unsuccessful (Owens et al., 1982); further experiments using burning as a countermeasure option were discontinued.

It must be emphasized that the techniques tested during these studies were ones for which there was an inadequate data base for Arctic environments. Other techniques, such as manual removal or the use of earth-moving equipment, have been well tested and documented in other environments; it was therefore considered unnecessary to retest these techniques specifically for Arctic situations.

## SUMMARY

The general conclusions described above represent the status of the project and the data interpretation after 3 years. A further field program is presently in the planning stages for 1983; it is hoped that subsequent sampling will be possible at intervals in the future. In particular, the presence of oil on the Bay 11 beach will provide a very valuable long-term study site to assess the persistence of stranded oil in a natural laboratory. Such an opportunity for long-term field measurements exists nowhere else in the Arctic at the present time and at very few locations in lower latitudes. The results obtained from the countermeasures experiments have provided an insight into the applicability and effectiveness of the techniques that were tested. The emphasis of the study has now shifted slightly to consider in more detail the persistence of oil stranded in the shore zone, in order to provide a suitable context within which to assess the decision on whether or not to clean up a contaminated shoreline. The existing data base for this type of assessment is not adequate at the present time and will require further monitoring and sampling.

The results that have been obtained from this Arctic environment are directly applicable to lower-latitude coastal environments. In particular, the results of the total hydrocarbon analyses from both the countermeasure and the control plots provide information that is directly relevant to sheltered low-energy environments in subarctic and temperate latitudes.

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# SESSION IV COUNTERMEASURES

# SESSION IV-A COMBUSTION AND INCINERATION

## DEVELOPMENT AND TESTING OF AN AIR-TRANSPORTABLE INCINERATOR

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### INTRODUCTION

An important part of an oil spill cleanup operation in a remote area is the capability to dispose of oil and the oiled debris in an environmentally acceptable manner. Burning such wastes at the recovery site offers the advantages of reducing the need for further handling through a high rate disposal process. Combustion units for this purpose would ideally be heli-transportable, of simple construction (requiring minimal field assembly), and able to dispose of a wide variety of oil spill debris.

Several devices have been developed to deal with this problem. A heli-portable flare burner has been successfully used to burn off recovered oil and emulsions (Buist and Vanderkooy, 1982). As well, the Trecan-PACE reciprocating kiln has been developed to clean oiled beach material (Gill and Stevens, 1980). Finally, an open pit type incinerator has been developed for the disposal of oiled debris (Lombard, 1979); however, the device is not easily transported, requiring ten helicopter lifts and considerable on-site assembly. For this project, a debris incinerator was developed with a primary design consideration of portability.

Most incinerators presently used for oil spill debris take their design from those commonly used in stationary industrial applications where weight and ease of assembly are not important design criteria. The main drawback with this type of incinerator is the excessive weight associated with the large quantities of refractory material used to line the firebox. As well, refractory material is relatively fragile and would not be durable under varied transport conditions.

Air-cooled steel walls have been suggested to eliminate the need for refractory lining (Petersen et al., 1975; Energetex, 1979). This type of design would have several advantages: air supplied to the chamber for combustion would be preheated. thus enhancing combustion; more importantly, by using hollow steel walls, an extremely light unit could be made. With these benefits in mind, a novel incinerator design was pursued thorugh small-scale laboratory testing, design of a full-scale prototype, and field testing of the full-scale unit.

### DESIGN CRITERIA

In order to be effective for the disposal of oil spill debris at remote locations, an incinerator must satisfy the following criteria:

a) lightweight construction: helicopter-transportable in no more than two loads of 950 kg;

b) simple and durable construction, requiring no precise alignment during field assembly;

c) reliable operation under a wide range of loading conditions: up to 1 tonne/h of weathered oil spill wastes.

### SMALL-SCALE LABORATORY TESTING

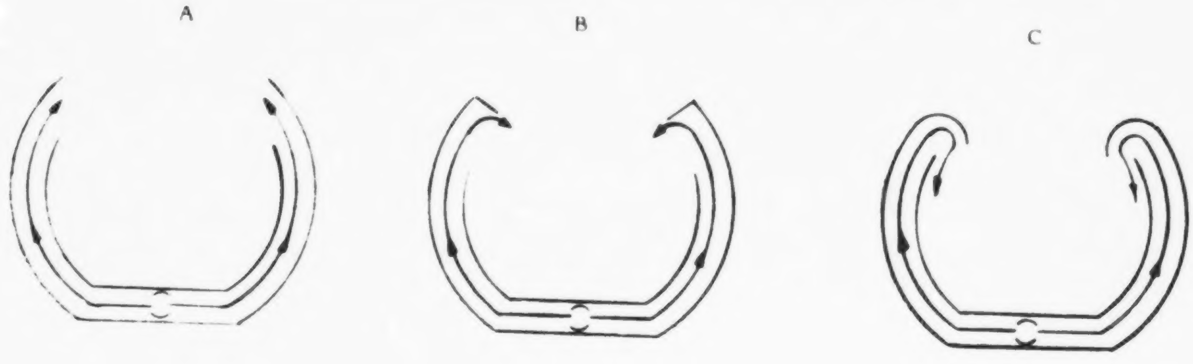
Small-scale tests were undertaken in order to select the best incinerator geometry. Three basic geometries were evaluated (Figure 1), air being supplied at the bottom, and circulating upwards for cooling and combustion. In these tests, only qualitative observations were made on combustion efficiency and cooling effectiveness.

Geometry A was found to be inadequate because the outside wall was not cooled sufficiently and was red hot after 20 min of operation. A portion of the air was escaping without being used for combustion; no recirculation was observed in the combustion chamber. Geometry B performed somewhat better but the air cooling was still inadequate. It was also observed that the air supply was not uniform, leading to some combustion instability. In order to improve cooling of the outside wall, the combustion chamber wall was extended upward (Geometry C). In tests of this model, the cooling problem was greatly reduced and the combustion was also satisfactory.

Based on these tests, instrumented models of Geometries B and C were built for further evaluation. These models were approximately 60 cm long and 40 cm in diameter. Combustion tests were conducted, monitoring the following parameters while varying the air flow and mass burning rates:

a) temperatures at various locations on the inside and outside walls;

b) general observations on combustion efficiency, smoke generation, flame shape and air distribution.



Air enters from the centre and circulates around the side

Top of the outside skin is bent inward to force more air into the combustion chamber

Top of the outside skin is curled over almost 180° while the inside skin is extended upwards

FIGURE 1 SMALL-SCALE UNIT GEOMETRY (→ air flow)

By comparing the two configurations, it was found that Geometry C resulted in lower wall temperatures and much cleaner combustion. It was therefore decided to base the full-scale design on Geometry C.

## PROTOTYPE DESIGN AND CONSTRUCTION

A prototype was designed using the results of the small-scale testing. In addition to the main design criteria listed earlier, several secondary characteristics seemed achievable:

a) low smoke generation (Ringleman No. 1 or No. 2);

b) uniform combustion;

c) low outer wall temperature (safety consideration and to prevent ground warming);

d) simple operation, requiring minimal support.

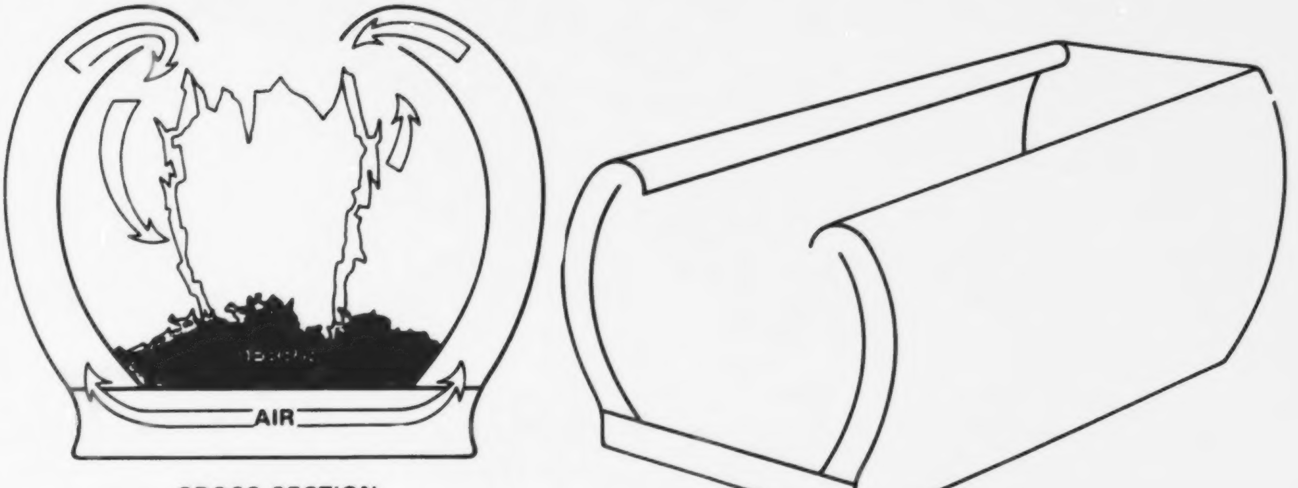
The cylindrical incinerator was 3 m long, 1.8 m wide, and 1.5 m high (Figure 2 shows a schematic diagram of the prototype). All parts for the combustion chamber were 304 stainless steel, No. 14 gauge for the outside skin and No. 10 gauge for the inner skin and end walls which would be subjected to higher temperatures. Four lifting hooks were installed, one at each corner, to facilitate lifting and air transportation. A hinged door was installed at one end to allow access for ash removal. The top of the combustion chamber is open to allow easy loading of wastes. Air is supplied through a duct at the bottom of the incinerator. Baffles in the duct provide a uniform distribution of air along its length.

The incinerator is equipped with a diesel-driven blower which can deliver up to 7,000 CFM, which is 120% of the air required for clean combustion. The blower is connected to the incinerator duct via a neoprene reinforced tube, allowing use on non-level ground. The diesel/blower is skid-mounted, weighs approximately 850 kg, and consumes approximately 8.0 L/h of diesel at full throttle. The entire unit can be transported by helicopter in two loads of approximately 850 kg each, and requires no special bracing or lifting harness.

## PROTOTYPE TESTING

Field tests were conducted to determine the operating limits of the full-scale design and to measure such parameters as smoke emissions and outside wall temperatures. The tests were carried out in Waterloo, Ontario, on February 2, 1983. The temperature was close to 0°C and a freezing drizzle was falling.

The incinerator and blower unit were transported to the test site on a flat-bed truck equipped with a hydraulic boom. After the units were placed on the ground, the flexible neoprene tube was slipped over the blower outlet and incinerator air duct and clamped in place. Figure 3 shows the assembled device. After supplying fuel and connecting the battery, the unit was ready for testing. Preparing the device for use had required only two men and had taken 10 minutes.



CROSS-SECTION

FIGURE 2 SCHEMATIC DIAGRAM OF INCINERATOR DESIGN

FIGURE 3 ASSEMBLED INCINERATOR PACKAGE, DIESEL/BLOWER AT LEFT

A mixture of straw and 3M Brand oil sorbent pads soaked in 3-weeks aged crude was prepared for burning. The mixture was placed in 60 garbage bags, each weighing 10 kg. Other materials obtained for burning were plain straw and firewood.

Incineration was started with several bales of hay, logs and crude oil brought in through the end door (Figure 4). The mixture was ignited with a match and a handful of straw, and was allowed to burn for less than 1 minute with the blower off. Once the fire had built up, the blower was started and semi-continuous loading of the incinerator began. Loading of the incinerator varied between 0.6 and 0.9 tonnes/h, with a variety of straw, wood and the prepared mixture of straw, sorbent pads and aged oil. The heating value of the feed mixture was estimated to be 13,000 BTU/lb.

The burning test was continued for 60 minutes. During this time, the smoke emission level remained between Ringleman No. 1 and No. 2 (Figures 5 and 6).

FIGURE 4 DEBRIS FOR START-UP LOADED THROUGH END DOOR

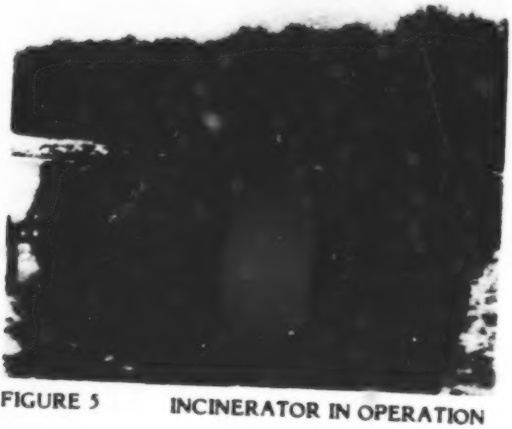


FIGURE 5 INCINERATOR IN OPERATION

FIGURE 6 INCINERATOR IN OPERATION - PUFF OF SMOKE AS DEBRIS IS LOADED

Thermocouples mounted at three locations on the incinerator unit provided temperature measurements during the test. The temperature of the end panel fluctuated between 220°C and 250°C, reaching a peak of 293°C. The end panels buckled slightly during the test burn, but this did not affect the performance. The temperature on the inside of the combustion chamber (measured near the end wall) varied greatly due to the variance in the flame location; a peak temperature of 1,045°C was recorded. As expected, the temperature of the outside wall remained low, reaching a peak of 10°C. Throughout the test the walls were, at most, warm to the touch. The incinerator had a negligible effect on the ground temperature: snow beneath the incinerator did not melt during the test.

After completion of the test, the end door was opened and the unburned ash was shovelled out from the outside. No significant warping of the inside walls was noted and the unit could have been used again immediately.

## CONCLUSIONS

The incinerator as designed and built is easily transportable in two loads of 850 kg each. Field assembly is minimal involving the use of an adjustable wrench and screwdriver and requiring only 10 minutes.

The incinerator is easily loaded through the end door for startup and thereafter over the side. A burning rate of up to 0.9 tonnes/h was achieved. The smoke emission levels at this rate were in the range of Ringleman No. 1 and No. 2. The temperature of the side walls and bottom of the incinerator was close to ambient throughout the testing. The end wall temperatures were much higher, but within the design limits of the material.

The field tests were successful, demonstrating achievement of the two main design criteria: low weight and a high rate of clean combustion. Further tests are planned for the summer of 1983 in the Arctic to test the endurance of the incinerator and to demonstrate its heli-portability.

## ACKNOWLEDGEMENTS

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# THE DEVELOPMENT AND TESTING OF A FIREPROOF BOOM

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## ABSTRACT

In situ burning of crude oil on water can be an extremely effective oil spill countermeasure, particularly in remote offshore areas and on cold water where conventional countermeasures are limited. In order for in situ burning to be an efficient mitigative technique, the oil must be contained and thickened. A novel fireproof boom has been researched, developed and tested that can:

a) survive, without damage, long-term exposure to the heat generated by burning crude oil in situ;

b) contain burning crude oil in at least Sea States of 2-3 and at current speeds up to 0.4 m/s without loss of combustion intensity;

c) survive, without damage, for periods of time at sea; and

d) withstand contact with small ice features.

This paper documents the results and conclusions of a 3-year, $500,000 fireproof boom study.

## INTRODUCTION

The Ixtoc I incident, the sinking of the ATLANTIC EMPRESS and the BURMAH AGATE spills provide evidence that it is possible to burn oil on open water with some success (Ross et al., 1979; Horn and Neal, 1981; Goodier and Siclari, 1981). Much work has been conducted on the fundamentals of in situ burning of oil both on ice and open water (e.g., Energetex, 1977, 1981; Arctic Canada, 1977; USDOE, 1979). One conclusion of this work has been that for oil to be efficiently burned in situ it must be contained and thickened. The use of in situ burning as an offshore oil spill cleanup technique offers a tremendous advantage over conventional containment, skimming, storage and disposal. The use of a fireproof boom would permit the containment and disposal of oil in one step using only one piece of equipment which, depending on the circumstances, could dispose of tens of thousands of barrels of oil per day (BOPD).

In the past, several studies in Canada (Purves and Daoust, 1978; Roberts and Chu, 1978; McAllister, 1979) have investigated the use of booms to contain and thicken oil so that it could be burned in situ on water. Each proposed design, however, failed to be an operationally feasible device for one reason or another.

As a result of work conducted on a fireproof boom constructed from empty drums, Dome Petroleum, through COOSRA, decided to undertake a project to research, develop, construct and field test a fireproof boom that had the following design criteria:

a) able to withstand flame temperatures of 980°C for extended periods of time in a saltwater environment and be reuseable;

b) able to contain burning oil in a "U" configuration in a Sea State 4 and survive Sea State 5;

c) be as compact as possible and remain flexible down to -20°C and storable to -50°C;

d) have good abrasion resistance so as to be able to withstand frequent handling and some contact with ice;

e) easily deployed using supply vessels and easily towed at 2 knots;

f) have a tensile strength of at least 110,000 Newtons (N).

This paper documents the 3-year program that was undertaken to develop the fireproof boom. Specifically, the initial design and subsequent towing, fire and test tank trials are discussed, followed by an analysis of the preliminary offshore trials. The paper concludes with a presentation of the final design of the boom and its potential for offshore oil spill cleanup.

### INITIAL BOOM DESIGN

In order to meet the design criteria, an extensive search for suitable materials of construction was instituted, using the paper by Roberts and Chu (1978) as a starting point. It became apparent that very few materials could meet the design requirements; only two were relatively inexpensive, these being high-chromium stainless steels, such as type 309 and 310 (Perry and Chilton, 1973), and a refractory blanket material manufactured by the Carborundum Company, "Fibrefrax L144", which is a cloth material woven with a Nichrome wire.

Using these materials, a 12 m section of prototype boom was constructed (Figure 1) which consisted of vented stainless steel flotation units with a pentagonal cross-section, a "sail" to provide freeboard, and a PVC-coated nylon skirt underwater to provide draft. The use of stainless steel at the waterline ensures high abrasion resistance. To provide wave conformation, each 1.5 m long flotation unit was joined to a 0.75 m long flexible panel constructed of stainless mesh-encased "Fibrefrax" blanket connected to a further section of PVC-coated nylon skirt.

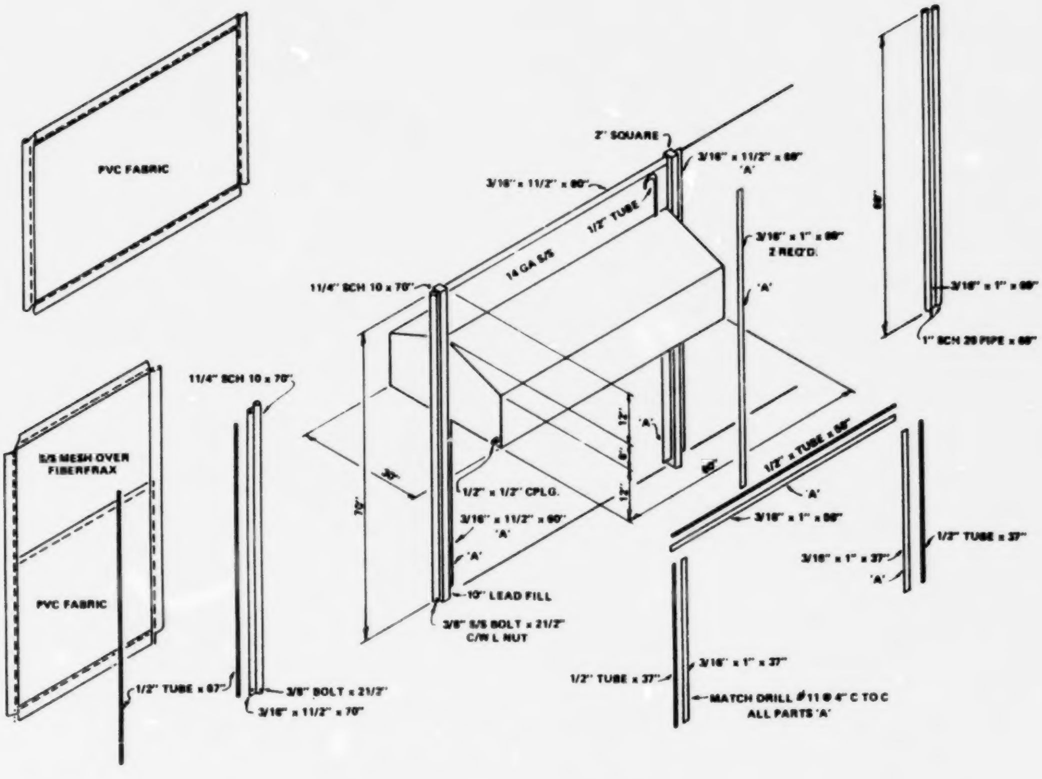
PVC FABRIC
2" SQUARE
3/16" x 11/2" x 69"
'A'
3/16" x 11/2" x 90"
1/2" TUBE
14 GA S/S
3/16" x 1" x 69"
2 REQ'D.
'A'
11/4" SCH 10 x 70"
69"
3/16" x 1" x 69"
1" SCH 20 PIPE x 69"
11/4" SCH 10 x 70"
S/S MESH OVER FIBERFRAX
PVC FABRIC
30"
70"
12"
6"
12"
'A'
60°
1/2" x 1/2" CPLG.
3/16" x 11/2" x 90"
'A'
'A'
10" LEAD FILL
3/8" S/S BOLT x 21/2" C/W L NUT
1/2" x TUBE x 56"
'A'
3/16" x 1" x 56"
1/2" TUBE x 37"
3/16" x 1" x 37"
'A'
1/2" TUBE x 67"
3/8" BOLT x 21/2"
3/16" x 11/2" x 70"
3/16" x 1" x 37"
1/2" TUBE x 37"
MATCH DRILL #11 @ 4" C TO C ALL PARTS 'A'

FIGURE 1 INITIAL FIREPROOF BOOM DESIGN

Tension members, consisting of 0.5 mm diameter stainless steel cables, were added to ensure no tension loads were placed on the flexible panels. The overall height of the boom was 1.77 m, with 0.66 m being the freeboard in calm water. Each section of the boom was connected by means of a sliding joiner. These joiners fit inside slotted pipes fastened to both the free end of a flexible panel and the end of the next flotation unit.

#### Towing Trials

Following successful static flotation trials that confirmed the stability of the flotation units, the boom was tow-tested in both straight-line and catenary configurations. The straight line tests revealed that the boom could be successfully towed at speeds up to 5 knots; however, the prop wash tended to deflect the first section of the boom at this speed. Also, a significant bow wave was set up by the first section, resulting in a high drag force on the boom. It was concluded that a towing paravane should be included in an operational model.

The catenary towing trials were held in a short, choppy sea, with wave heights of approximately 1 m and a wind speed of 30 km/h. The boom conformed well to the waves, demonstrated excellent stability, and was only overtopped once by a small amount of spray from a breaking wave.

Following these trials, it was discovered that the "Fibrefrax" material had been seriously eroded by the action of the waves; it was concluded that the flexible panels, as originally designed, would not contain oil.

### Flexible Panel Redesign

Following a further investigation of suitable construction materials, it was decided that the flexible panels should be built from thin gauge (0.4 mm) type 321 stainless steel sheet that had been corrugated to provide the required flexibility (Figure 2). These panels were fitted to the boom and a second towing trial confirmed that they did have the required flexibility. As redesigned, each boom section now had a weight of approximately 125 kg, a gross buoyancy of approximately 440 kg, and a buoyancy-to-weight ratio of 3.5:1.

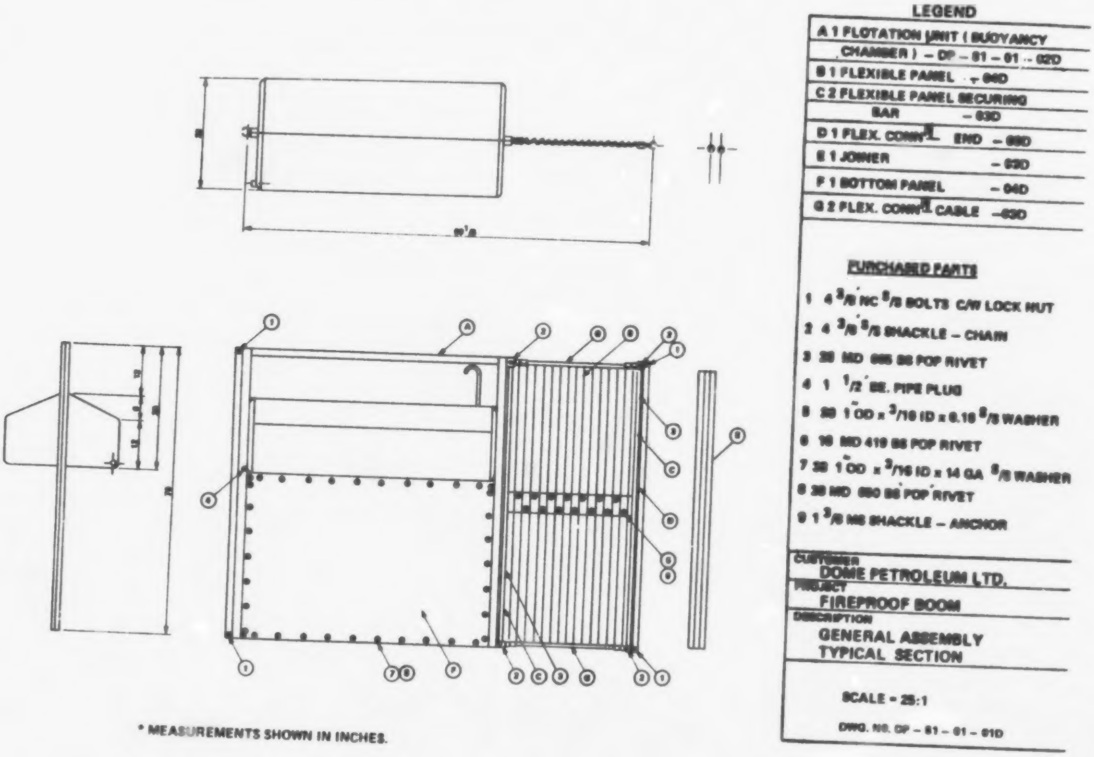
LEGEND
A 1 FLOTATION UNIT ( BUOYANCY CHAMBER ) – DP – 81 – 01 – 02D
B 1 FLEXIBLE PANEL – 06D
C 2 FLEXIBLE PANEL SECURING BAR – 03D
D 1 FLEX. CONN END – 05D
E 1 JOINER – 03D
F 1 BOTTOM PANEL – 04D
G 2 FLEX. CONN CABLE – 03D
PURCHASED PARTS
1 4 3/8 NC 5/8 BOLTS C/W LOCK NUT
2 4 3/8 5/8 SHACKLE – CHAIN
3 20 MD 685 SS POP RIVET
4 1 1/2 BE. PIPE PLUG
5 20 1 OD x 3/16 ID x 0.18 5/8 WASHER
6 16 MD 419 SS POP RIVET
7 20 1 OD x 3/16 ID x 14 GA 5/8 WASHER
8 20 MD 650 SS POP RIVET
9 1 3/8 MS SHACKLE – ANCHOR
CUSTOMER
DOME PETROLEUM LTD.
PROJECT
FIREPROOF BOOM
DESCRIPTION
GENERAL ASSEMBLY
TYPICAL SECTION
SCALE = 25:1
DWG. NO. DP – 81 – 01 – 01D
A
B
C
D
E
F
G
1
2
3
4
5
6
7
8
9
* MEASUREMENTS SHOWN IN INCHES.

FIGURE 2 REVISED DESIGN WITH CORRUGATED STEEL CONNECTORS

## STATIC BURNING TRIALS

In order to confirm that the design of the boom and the materials selected would withstand the temperatures of a crude oil fire, that no corrosion problems would occur, and to investigate the continuous combustion of crude oil on water, a burning trial was held December 12, 1980, near Port Mellon, B.C. (McAllister and Buist, 1980).

The boom, with the redesigned flexible panels, was connected in a circle and secured inside an area encircled by 0.9 m inshore boom and fender logs, as shown in Figure 3. Thermocouples were mounted at various locations on one section of the boom and were monitored from a barge which was placed adjacent to the test site for use as a logistics and observation platform. Nine drums of Redwater crude oil (specific gravity = 0.839 @ 26°C, viscosity = 8 mPas @ 21°C) supplied by Imperial Oil were also placed on the barge, and a pump and hose were provided to pump the oil continuously under the skirt of the fireproof boom.

FIGURE 3 STATIC BURNING TRIALS

After a slick of 2-3 mm thickness had been pumped into the area enclosed by the fireproof boom, it was ignited by a burning sorbent pad soaked in oil. Over a 2-hour burning period, 1,545 L of crude were pumped into the boomed area. At the completion of the trial, only 2 L of oil residue remained within the boom, resulting in a burn efficiency of 99.87% and a slick regression rate of 2.3 mm/min. Analysis of the burn residue revealed that it had a specific gravity of 0.933; before and after analysis of the water column and sediments did not detect conclusive differences in hydrocarbon concentrations. Both these results led to the conclusion that no oil was lost to the water column during the burns.

The temperatures measured at various points on and around the boom are shown in Figure 4. The maximum temperature measured was 905°C, well within the design maximum exposure temperature of 980°C.

It is interesting to note that the inside boom skin temperature was consistently recorded as higher than the temperature just above the slick. This may either be a calibration error or a reflection of the fact that, due to oxygen starvation, the combustion process was taking place at the edges of the boom and in the air space above it rather than immediately above the slick.

The thermocouples located in the water below the fire (No.'s 1 and 2 on Figure 4) indicated that although some heat was being transferred to the water, it was not raising the water temperature appreciably, even 4 cm below the burning slick. Presumably, much of the heat transferred into the water column was being absorbed in boiling off a thin surface layer of water. This was evidenced by observations of some droplet carryover during the combustion, normally caused by boiling, and the fact that the surface water in close proximity to the flame could be observed to be boiling during gusts of wind that bent the flame over the side of the boom.

The smoke plume generated by the burn rose vertically to a height of approximately 300 m and then dispersed horizontally, with visible smoke disappearing within 2-3 km downwind.

When the fire had extinguished itself, the boom was examined and found to be in good structural condition. Some of the sheet metal was slightly warped, and the exposed surfaces were covered with droplets of a hard asphaltic residue caused by the aforementioned droplet carryover. On removal from the water, no further damage was observed and the boom was considered ready for immediate re-use.

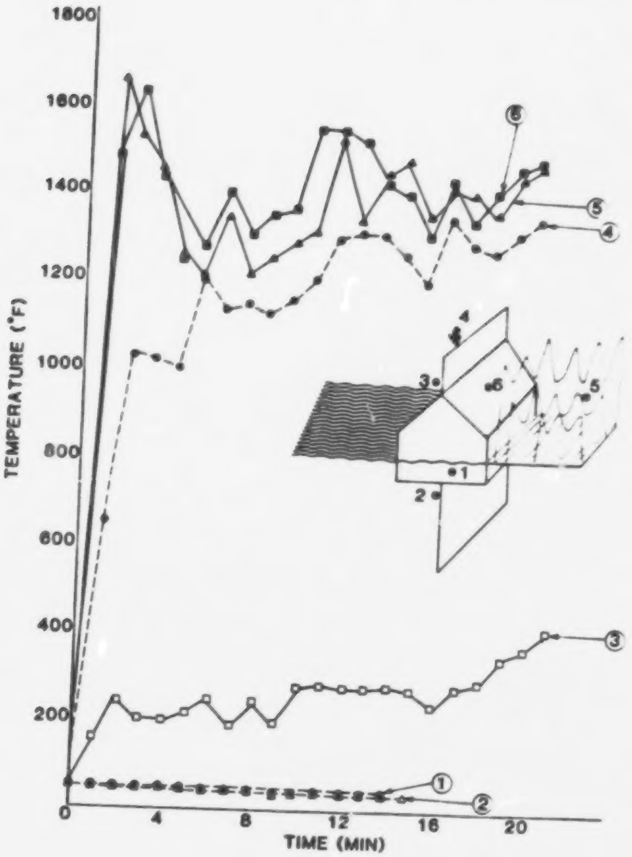

FIGURE 4 BURNING TRIAL TEMPERATURE PROFILES

## OHMSETT TRIALS

Following the burn trials, the prototype boom was tested at the U.S. Environmental Protection Agency Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility to further confirm its towing and stability characteristics, define its oil containment characteristics in controlled wave and current conditions, and investigate the effects of waves and currents on in situ combustion (Dome, 1981).

Two oils were utilized for the testing, a Circo 4X light oil (specific gravity = 0.9, viscosity = 11 mPas @ 22°C) for the containment trials and Murban crude oil (specific gravity = 0.85, viscosity = 9 mPas @ 14°C) for the in situ combustion trials. Table 1 summarizes the test matrix and the results obtained from the program. As can be seen, the boom exhibited excellent stability in all the wave conditions tested and was found to contain oil at speeds up to 0.4 m/s (0.75 knots). As this speed, a vortex formed between adjacent flotation units drew small quantities of oil beneath the skirts. The anomalous containment of oil by the boom at up to 1.25 m/s tow speeds observed in Runs 3R, 4 and 19 was presumably due to the small volumes of oil used in these runs.

Runs 8, 9, 10 and 19 showed that in calm conditions, the combustion was not adversely affected by increased tow speed up to 1 m/s. However, it is probable that had larger volumes of oil been used, the combustion efficiency would be reduced due to entrainment of the oil beneath the boom at speeds exceeding 0.5 m/s. A comparison of runs 8, 18, 14 and 15 shows that increasing swell height did not affect the ability to ignite the slick or the intensity of the resulting in situ combustion (Figure 5). However, it was observed that the amount of residue left increased with increasing swell height. This was a function of the relatively small volumes of oil used in these trials and is not expected to seriously affect overall combustion efficiencies on a large scale.

The results of runs 15 and 16 illustrate that in the swell wave condition, the intensity of the burn was not affected until the tow speed reached 0.5 m/s (1 knot), at which point it was drastically reduced, presumably by the turbulence set up inside the catenary by the small waves reflected off the boom at this speed.

Of the three runs done in harbour chop (11, 11R and 11R'), ignition was only achieved once (11R') by increasing the oil volume and using two igniters. The flame spread was slow and the combustion poor. A breaking wave extinguished the flames before the entire surface area of the slick was ignited.

TABLE 1 TEST MATRIX AND RESULTS

| Test No.[a] | Tow Speed (m/s) | Wave | | Wind | | Oil (L) | Remarks |
|---|---|---|---|---|---|---|---|
| | | Type | Height x Length (m) | Speed (m/s) | Direction | | |
| 1 | 0.25 - 1.0 | calm | - | - | - | - | stable in catenary; no rolling |
| 2 | 0.25 - 1 | swell | 0.4 x 19 | - | - | - | stable, good wave conformance; no rolling |
| 3 | 0.25 - 2.0 | calm | - | - | - | Circo (75) | first loss at 0.4 m/s at vortex between floats; oil kept from boom by reflected waves |
| 3R | 0.25 - 1.25 | calm | - | 5 | NE | Circo (38) | required 1.25 m/s to flush oil; at lower speeds, oil was not touching boom; first loss at 0.4 m/s, as in 3 |
| 4 | 0.25 - 1.0 | swell | 0.4 x 19 | 5 | NE | Circo (75) | first loss at 0.8 m/s; oil held out from boom by float backwash |
| 7 | 0.25 - 1.0 | harbour chop | 0.2 | 5 | NE | Circo (75) | first loss at 0.4 m/s; oil dispersed by turbulence in catenary |
| 8 | 0.25 | calm | - | 8 | NE | Murban (38) | intense burn for 5 min; estimated greater than 90% efficiency; probably only 10 L of Murban, not 38 |
| 9 | 0.15 | calm | - | 8 | NE | Murban (38) | intense burn for 5 min 51 s; estimated same efficiency as 8 |
| 10 | 0.35 | calm | - | 12 | WNW | Murban (38) | flames had some difficulty spreading upwind; intense burn after 4 min 43 s |
| 11 | 0.25 | harbour chop | 0.2 | 12 | WNW | Murban (38) | no ignition of oil, igniter pushing oil away by bobbing |
| 11R | 0.25 | harbour chop | 0.2 | 12 | WNW | Murban (38) | no ignition of oil using flare |
| 18 | 0.25 | swell | 0.2 x 19 | 12 | WNW | Murban (38) | ignited in calm condition; intense burn for 3 min 39 s, more residue than 7, 8 and 9 |
| 14 | 0.25 | swell | 0.4 x 19 | 12 | WNW | Murban (38) | ignited in calm condition; intense burn for 2 min 29 s, more residue than 18 |
| 15 | 0.25 | swell | 0.4 x 19 | 12 | WNW | Murban (57) | ignited in waves; intense burn for 2 min 54 s, approx. same residue as 14 |
| 16 | 0.35 - 0.5 | swell | 0.4 x 19 | 12 | WNW | Murban (57) | ignited in waves; intense burn for 2 min at 0.35 m/s, poor burn for 1 min 59 s @ 0.5 m/s |

TABLE 1 TEST MATRIX AND RESULTS (cont'd)

| Test No.[a] | Tow Speed (m/s) | Wave Type | Wave Height x Length (m) | Wind Speed (m/s) | Wind Direction | Oil (L) | Remarks |
|---|---|---|---|---|---|---|---|
| 19 | 0.35 - 1 | calm | - | 10 | W | Murban (57) | intense burn for 3 min 10 s; no difference in burning with increased speed |
| 11R' | 0.25 | harbour chop | 0.2 | 7 | S | Murban (57) | successful ignition; pool flame spread; poor combustion extinguished by breaking wave |
| 20 | 0.25 | calm | - | 7 | S | Murban (57) | emulsified oil from 11R' successfully burned for 7 min 10 s |
| 21 | 0.25 - 0.75 | calm | - | 7 | S | Circo (380) | first loss at 0.4 m/s through vortex; extensive loss by entrainment at 0.5 m/s |
| 22 | 0.25 - 1 | harbour chop | 0.6 m | 7 | S | | durability trial - survived well; excellent stability - minor damage to skirt observed on removal |

[a]For identification only, not necessarily consecutive order.

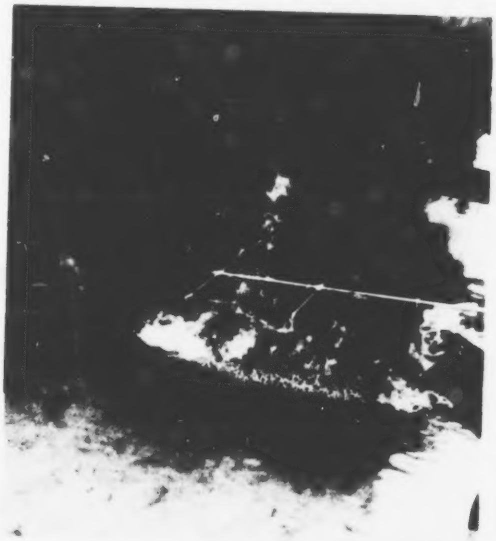

FIGURE 5 IN SITU BURNING IN WAVES AND CURRENT

Upon removal of the boom, the only damage observed to have occurred was the loss of six rivets, resulting in the slight bending of one of the skirt holding rods, and in some wear on the upper flexible panel tension cable securing points.

## PRELIMINARY OFFSHORE TRIALS

As a result of the successful test tank trials, 25 additional sections (60 m) of boom were constructed. This version of the boom incorporated several minor modifications, including rounded corners on the flotation sections, replacement of the PVC skirt beneath the flotation with stainless steel sheet, and reinforcement of the tension cable securing points. A towing paravane was also constructed.

In September, 1981, the boom was deployed near Mulgrave, Nova Scotia and towing trials were undertaken (Figure 6). The results, illustrated in Figure 7, indicated that the drag force on 55 m of boom was approximately 3,800 N at a speed of 2 knots. The boom followed the waves well and did not roll appreciably.

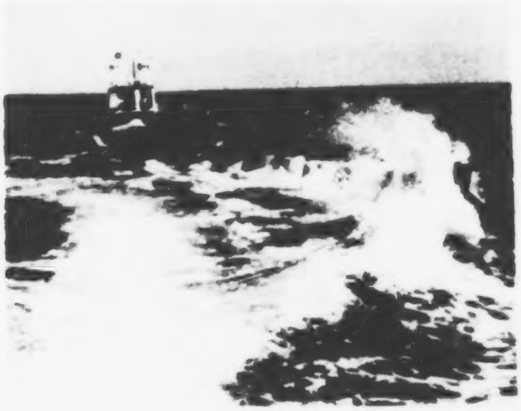

FIGURE 6 BOOM TOWING AND WAVE RESPONSE TRIALS

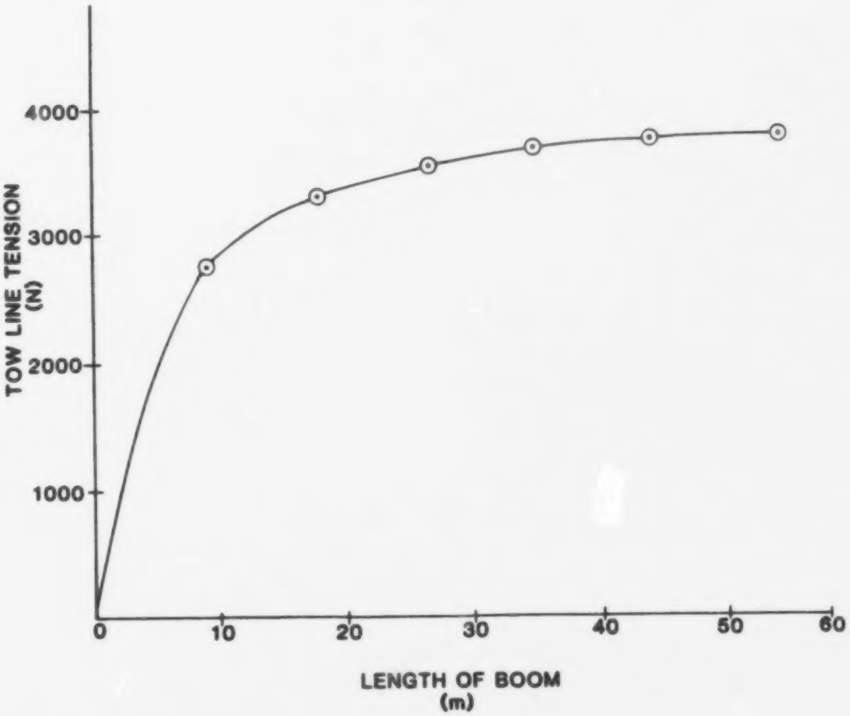

FIGURE 7 RESULTS OF 2 KNOT TOWING TEST (STRAIGHT-LINE TOW BEHIND WORKBOAT)

Following the tow tests, the boom was anchored in a catenary on Chedabucto Bay (Figure 8). After 24 hours exposure to Sea State 3-4 with a 4-s wave period, it was noted that several of the flexible panels had cracked vertically. It was initially thought that this was due to relative vertical motion of adjacent flotation units as waves passed beneath the boom. As such, the boom was recovered and a "cross-cable" arrangement installed to restrict this vertical motion (Figure 9) and the boom was redeployed. However, the cracks continued to appear. Metallurgical analysis revealed that the failure was due to stress cracking caused by the "flapping" motion of the flexible panel. In a 24-h exposure to a 4-s wave, the connector "flapped" some 22,000 times.

FIGURE 8 BOOM DEPLOYED OFFSHORE

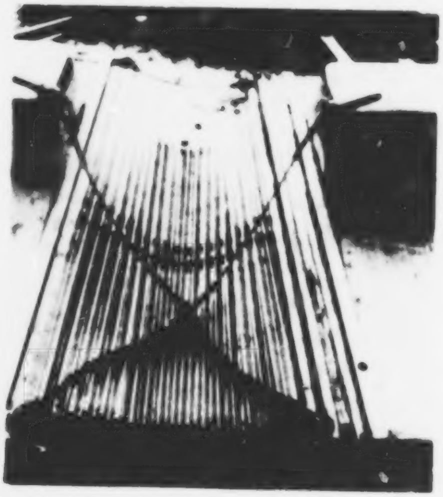

FIGURE 9 CROSS CABLES

In order to overcome this problem, a more robust flexible connector was designed. This connector consists of a sheet of pleated, light-gauge stainless steel through which is passed a universally jointed box beam to provide tensile strength to resist towing and ice loads (Figure 10). The pleat bends are reinforced by the addition of a tubular backing and are of a sufficient radius to reduce stress concentrations to well below the material's endurance limit. The relative vertical motion of two adjacent flotation sections is restricted by the use of a guide shoe mounted on the universally jointed tongue. Stainless steel hinges on either end of the connector permit the boom to form a curve to contain oil.

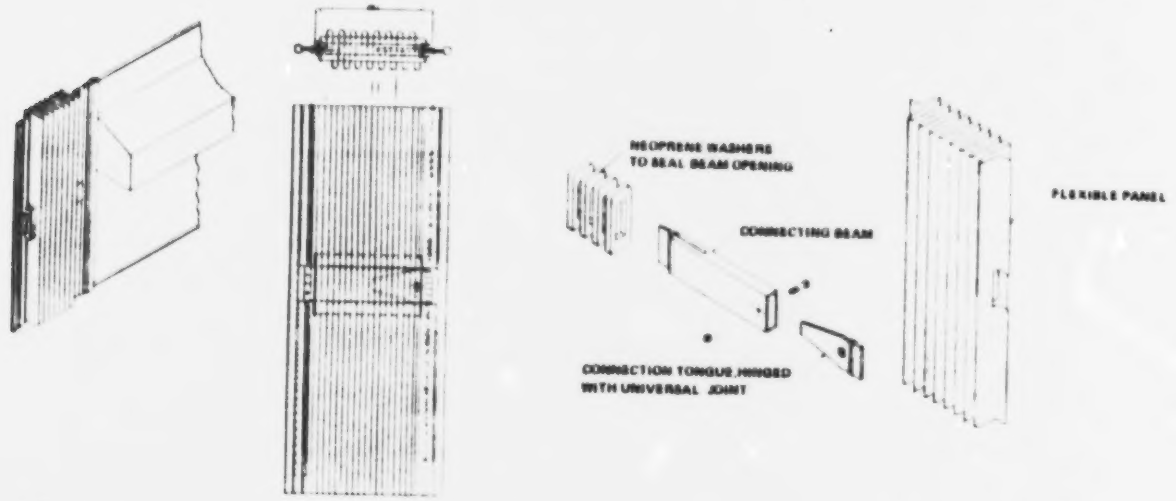
NEOPRENE WASHERS TO SEAL BEAM OPENING
FLEXIBLE PANEL
CONNECTING BEAM
CONNECTION TONGUE,HINGED WITH UNIVERSAL JOINT

FIGURE 10 REVISED CONNECTOR DESIGN

Extensive bench testing of this connector was performed in a jig specially constructed to simulate the action of waves on the connector (Figure 11). The design finally selected was subjected to 302,232 cycles over a period of 10 days (equivalent to approximately 25 days in 4-s waves) without any sign of fatigue or damage.

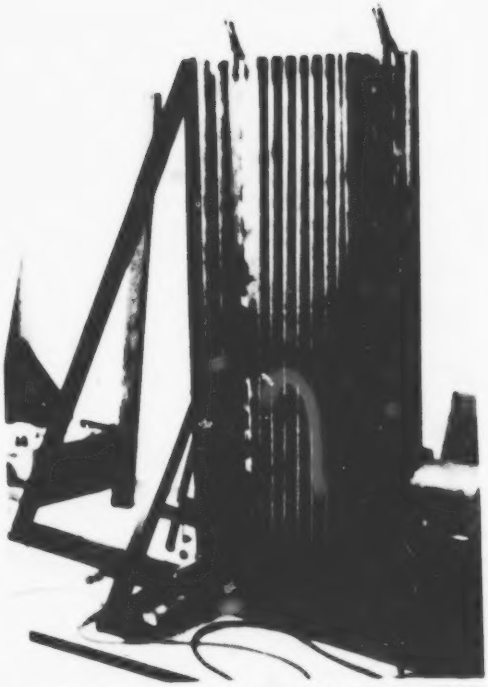

FIGURE 11 BENCH TESTING OF FINAL CONNECTOR DESIGN

## FINAL OFFSHORE TRIALS

For a final durability test, 60 m of the redesigned boom were deployed off Roberts Bank Superport near Vancouver, B.C., and anchored at each end. This boom consisted of 19 connectors of the revised design and 20 flotation units modified to accept these connectors. After 3 days of moderate sea conditions, it was discovered that vandals had cut an anchor rope, causing one end of the boom to tie itself in a knot, submerging several sections in the process. The boom was towed back to shore for damage assessment. The damage included several bent joiners, damage to several pleated sections due to the boom overriding itself (Figure 12), numerous dents to the flotation sections, and the loss of several pleat backing tubes.

FIGURE 12 DAMAGE TO PLEATED SECTION DUE TO BOOM OVERRIDING ITSELF

Since the damage was not serious, it was decided to redeploy the boom without making repairs, but a series of storms prevented immediate redeployment. Upon receiving a favourable forecast, the boom was reassembled on the beach. However, the weather continued to be unfavourable and the boom was trapped in the surf zone of the pebble cobble beach where it was battered by a series of storms over the next several days (Figure 13). This resulted in considerable denting and bending of the flotation units and flexible connectors. In order to ensure a vigorous test of the boom's durability, it was redeployed "as is".

The boom was finally redeployed on November 2, again anchored at each end. Over the next 17 days, the waves ranged from 0.5 m with a 2-s period of 2 m with a 4-s period. The winds during this time were as high as 60 km/h. On November 7, it was noted that the wave action was more severe when the boom was not in tension; one end was therefore released and the boom allowed to weatherware. On November 19, the boom was subjected to a series of towing trials as a final test; it performed well (Figure 14).

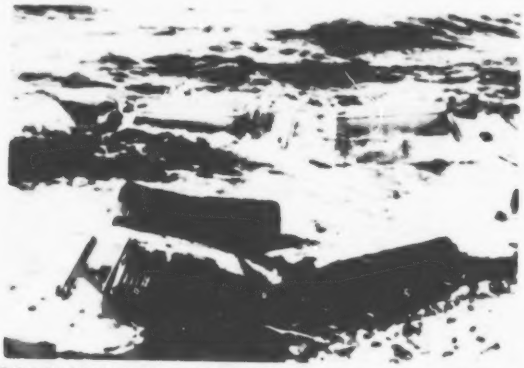

FIGURE 13 BOOM SECTIONS ON THE BEACH BEING BATTERED BY THE SURF

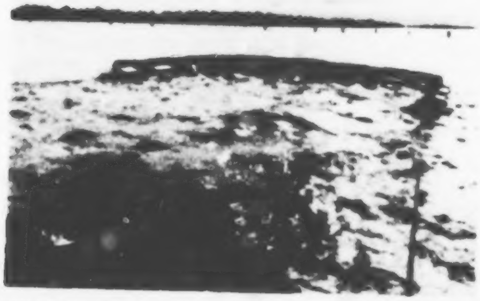

FIGURE 14 TOWING TRIALS CONDUCTED PRIOR TO RETRIEVAL

Upon removal from the water, each float and connector was thoroughly inspected; the following general observations were made:

a) despite the tremendous abuse that the boom had undergone, it was still operational upon retrieval;

b) while obviously damaged, particularly on the bottom and sides where backing tubes were missing, the connectors still permitted the boom to move freely and would have contained oil;

c) minor cracks were found in some pleats, but only in those missing backing tubes;

d) there was no appreciable damage to either the flotation units or the paravanes.

Based on the observations of the final durability trials, several modifications were recommended, including sealing the flotation vent tubes with wax to prevent possible flooding, attaching the pleat backing tubes more securely (with three or more rivets), and reducing the height of the pleated section to prevent damage to the bottom of the sheeting. The final design of the fireproof boom has the following major characteristics: section weight, 210 kg (boom and connector); section length, 2.58 m; linear weight, 81 kg/m; gross buoyancy, 440 kg; buoyancy/weight ratio, 2.1 to 1; draft, 1.2 m; freeboard, 0.57 m. It should be noted that this fireproof boom has been designed to operate and survive severe offshore conditions. Such booms for use in less severe conditions could be dramatically less massive.

## POTENTIAL FOR OFFSHORE IN SITU BURNING

The existence of an offshore boom capable of operating and surviving on the sea for extended time periods offers an efficient new technique for oil spill cleanup. In situ burning is a one-step removal process that can dispose of large volumes of oil on water. Based on the results of trials with the fireproof boom, Figure 15 illustrates the dependence of oil combustion rate on burning area. In an area of only some 2,000 $m^2$, 6,600 $m^3$ of oil could be burned daily.

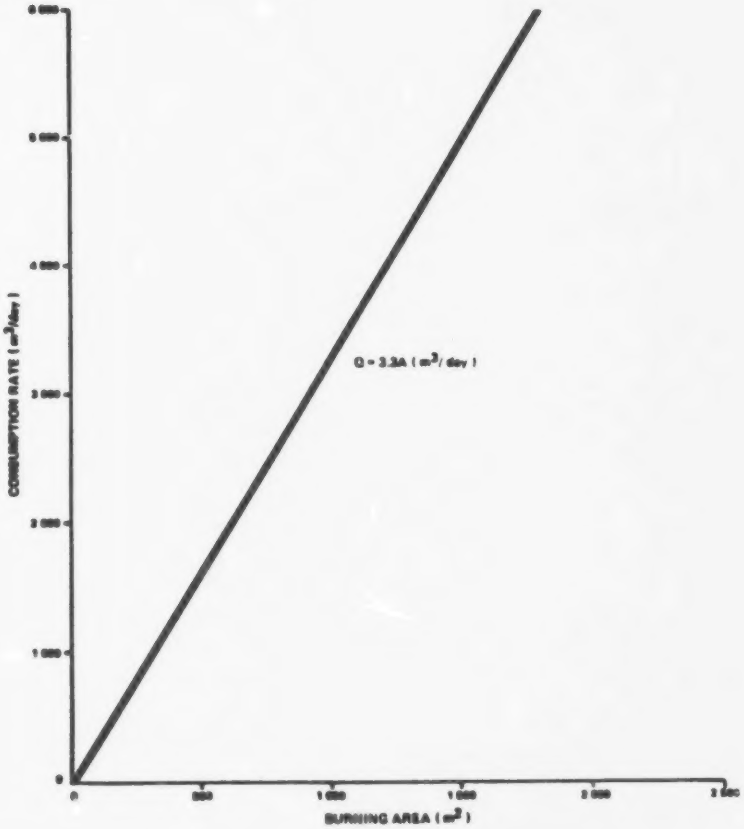

FIGURE 15 IN SITU BURNING OIL CONSUMPTION RATE

Assuming that the boom, when deployed in a current, takes the shape of a half ellipse, the length of boom required to contain a certain burning area can be calculated as follows:

a) Slick burning rate:

$$Q = rA' = 3.8 \times 10^{-5} A' \qquad (1)$$

Where

$Q$ = oil burning rate ($m^3/s$)

$A'$ = slick area on fire ($m^2$)

$r$ = slick regression rate

= 2.3 mm/min or $3.8 \times 10^{-5}$ m/s

b) Area of half-ellipse:

$$A = \pi ab/2 \qquad (2)$$

Where

$A$ = Area of half-ellipse ($m^2$)

$a$ = length of semi-major axis of ellipse (m)

$b$ = length of semi-minor axis of ellipse (m)

c) Perimeter of half-ellipse:

$$X = \pi\left(1/2(a^2 + b^2)\right)^{1/2} \qquad (3)$$

Where

$x$ = perimeter of half-ellipse or length of fireproof boom (m)

For oil leaking at a rate $Q'$ ($m^3/s$) onto water moving at a velocity of $U$ (m/s), the thickness $t$ (m) at a width of $2b$ (m) is:

$$t = Q'/2Ub \qquad (4)$$

Since the minimum slick thickness to support in situ combustion of fresh oil on water is 1 mm, this thickness must not be exceeded before the oil enters the boomed area. Rearranging equation 4 with $t = 0.001$ yields:

$$b = 500\,Q'/U \qquad (5)$$

To optimize the length of boom required, the slick area on fire should be the same as the area contained by the fireproof boom ($A = A'$), and the oil burning rate should equal the oil leak rate ($Q = Q'$). Rearranging equation 2 yields:

$$a = 2A/\pi\, b \qquad (6)$$

Substituting equation 5 into equation 6 gives:

$$a = AU/250\,\pi\, Q \qquad (7)$$

Substituting equation 1 into equation 7 yields:

$$a = 33.5U \qquad (8)$$

Finally, substituting equations 5 and 8 into equation 3 gives:

$$X = \pi\left(1/2\left(1100\,U^2 + \left(\frac{500\,Q}{U}\right)^2\right)\right)^{1/2} \qquad (9)$$

Figure 16 illustrates the lengths of boom required for three burning rates as a function of current speed. As an example, surface statistics for the southern Beaufort Sea are superimposed on Figure 16. It can be seen that 250 m of fireproof boom would be sufficient to combust 5,000 BOPD in excess of 80%, 15,000 BOPD for 75%, and 30,000 BOPD for approximately 50% of the open-water period.

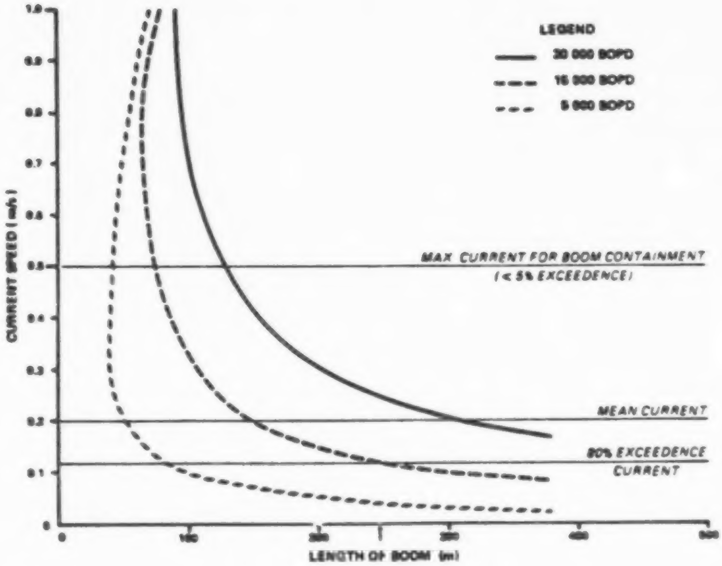

FIGURE 16 LENGTHS OF BOOM REQUIRED

Figure 17 illustrates one possible configuration for use of the boom in response to a blowout offshore. A conventional offshore boom is anchored or held by supply vessels to direct the oil toward a "pocket" of fireproof boom. As the oil moves toward this "pocket", it thickens; however, the overall slick thickness will not exceed 1 mm until the oil enters the "pocket". As the oil moves toward the back of the "pocket", it continues to thicken until it reaches the burning slick and ignites.

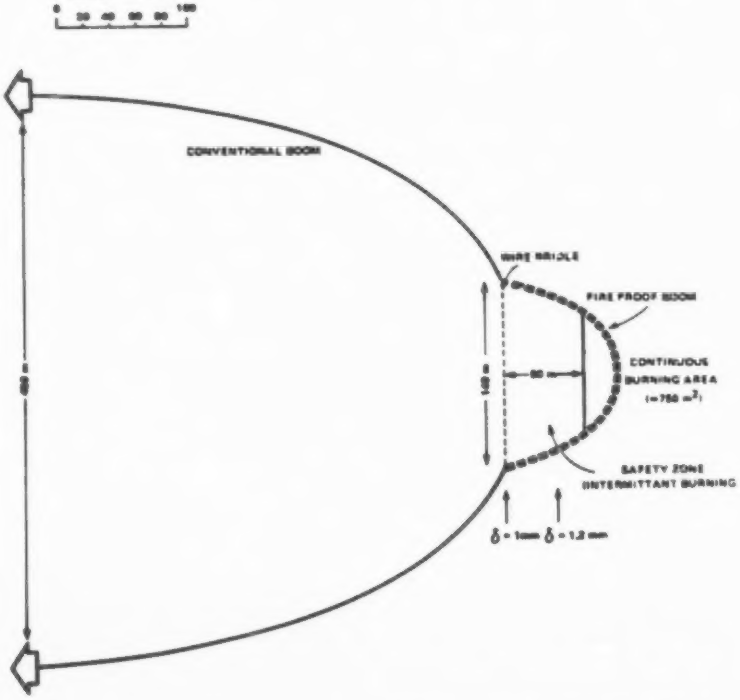
SCALE
0
20
40
60
80
100
CONVENTIONAL BOOM
WIRE BRIDLE
FIRE PROOF BOOM
CONTINUOUS
BURNING AREA
SAFETY ZONE
(INTERMITTANT BURNING
δ = 1mm
δ = 1.2 mm

FIGURE 17 EXAMPLE OF BOOM CONFIGURATION (15,000 bbl oil/day)

## CONCLUSION

A durable offshore fireproof boom has been researched, developed and tested that can:

a) survive, without damage, long-term exposure to the heat generated by burning crude oil in situ;

b) contain burning crude oil in at least Sea States 2-3 and at current speeds up to 0.4 m/s without loss of combustion intensity;

c) survive, without damage, for long periods at sea; and

d) withstand contact with small ice features.

Although the boom is necessarily massive, it offers a significant advantage over conventional offshore spill cleanup systems in that it can collect and dispose of large flowrates of oil in one self-sustaining step with a minimum of logistics support. Once the final offshore trials are complete, the boom will be commercially available.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of the Canadian Offshore Oil Spill Research Association (COOSRA); Environment Canada's Arctic Marine Oilspill Program (AMOP); the Canadian Coast Guard; and the Alaskan Beaufort Sea Oilspill Response Body (ABSORB).

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# SESSION IV-B CONTAINMENT AND RECOVERY

## ARCTIC FIELD TESTING OF THE LOCKHEED CLEAN SWEEP AND VEP ARCTIC SKIMMER

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### INTRODUCTION

In response to an oil spill in open water, the most conventional and widely used countermeasure is that of containing the spilled oil within booms and physically recovering it using mechanical skimmers. This paper presents the results of Arctic field trials of two such skimming devices: the Lockheed R2003 "Clean Sweep" skimmer, and the Versatile Environmental Products (VEP) "Arctic Skimmer".

Each of these skimmers had been previously tested by Environment Canada (Solsberg et al., 1976; Abdelnour et al., 1980) and by the Environmental Protection Agency (Clean Sweep - Griffiths, 1976; Arctic Skimmer - Lichte and Breslin, 1979), including trials in a test tank and a harbour environment. As well, the Clean Sweep has been tested in a test tank simulating a broken ice field (Schultz, 1976). These skimmers had not been extensively tested, however, under actual nearshore conditions. Field trials were therefore proposed in order to fulfill the following objectives:

a) to compare the two skimmers with respect to operation, recovery capabilities, and general considerations such as mooring and stability.

b) to quantify their recovery rates in an open-water environment.

### Skimmers: Principle of Operation

The Lockheed Clean Sweep utilizes a series of oleophilic discs to recover oil. The pickup mechanism consists of 38 parallel aluminum discs mounted concentrically on an open topped horizontal shaft (Figure 1). As the discs rotate (leading edge rotating downwards), they collect oil on their surface and turn through the water. At the top of the discs' rotation, the oil is wiped off and it falls into the open topped shaft. Inside the shaft, a screw conveyor moves the oil to a collection sump, where it is pumped to a support vessel.

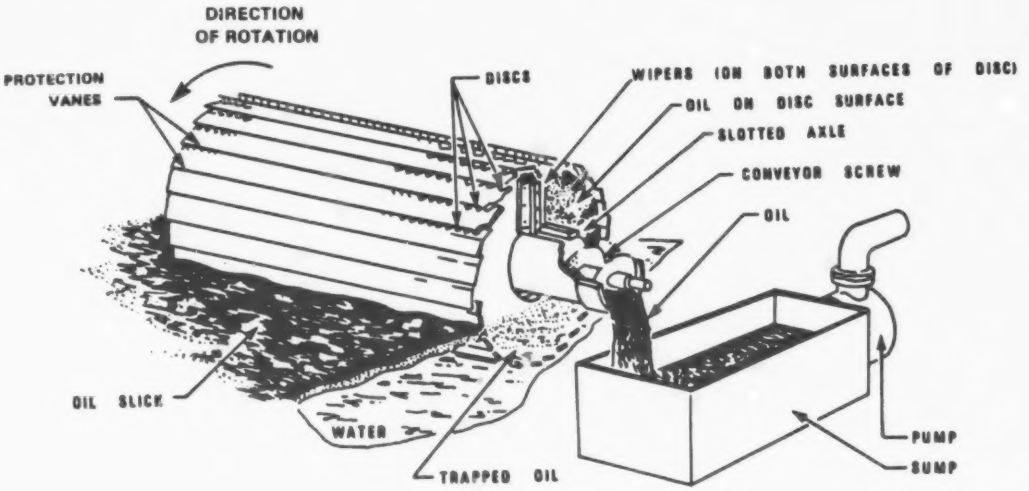

FIGURE 1 CLEAN SWEEP SKIMMER - PRINCIPLE OF OPERATION

The Arctic Skimmer utilizes an endless sorbent belt for oil recovery. The floating oil layer flows over the bow ramp and into the interhull area where it contacts the recovery belt (Figure 2). The belt carries the oil below the water surface, utilizing the buoyant force of the oil to ensure close contact of the oil layer and the belt. Oil removal from the belt is achieved using a perforated squeeze belt which squeezes over the large surface area of the head roll. The oil falls into a collection trough from which it is pumped into a support vessel.

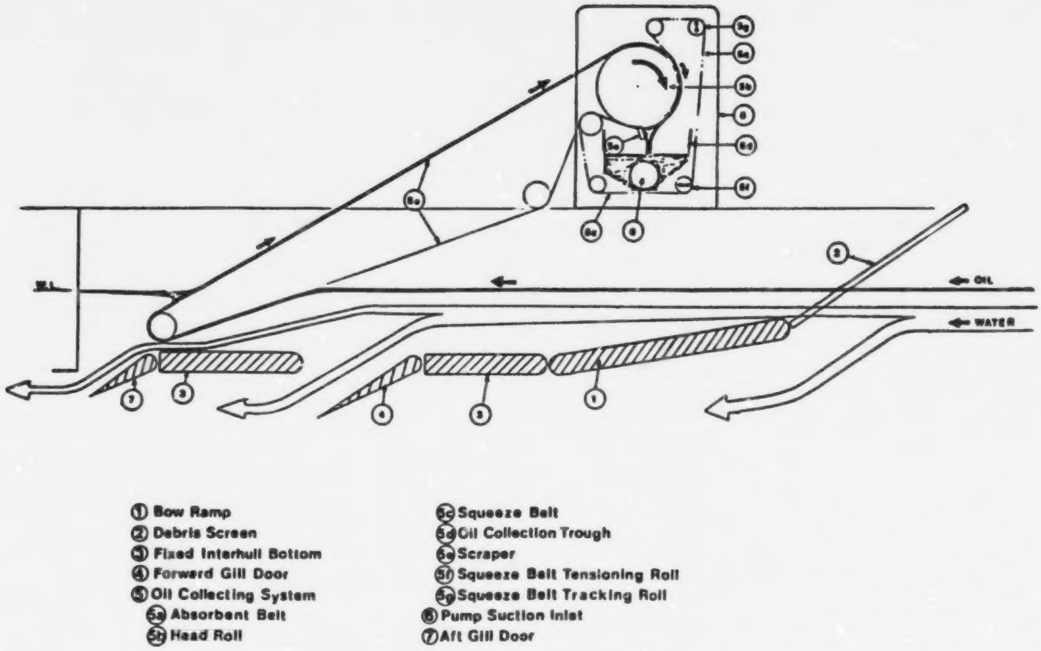
W.L.
OIL
WATER
① Bow Ramp
② Debris Screen
③ Fixed Interhull Bottom
④ Forward Gill Door
⑤ Oil Collecting System
(5a) Absorbent Belt
(5b) Head Roll
(5c) Squeeze Belt
(5d) Oil Collection Trough
(5e) Scraper
(5f) Squeeze Belt Tensioning Roll
(5g) Squeeze Belt Tracking Roll
⑥ Pump Suction Inlet
⑦ Aft Gill Door

FIGURE 2 ARCTIC SKIMMER - PRINCIPLE OF OPERATION

## EXPERIMENTAL METHODS

### Test Site

The site used for the trials was located just south of Tibjak Point at approximate coordiantes 69° 45'N; 133° 03'W (Figure 3), with a water depth of 2.5 m. This site was an excellent one for the experiment, being within 10 nautical miles of Tuk base and affording good protection from winds from either the NE or SE quadrants. The necessary approvals were obtained under the Ocean Dumping Control Act (ODCA - Environment Canada) and under the Arctic Waters Pollution Prevention Act (AWPPA - Indian and Northern Affairs).

### Equipment Setup

The following is a summary of the vessels used in the experiment:

| | | |
|---|---|---|
| Beaufort Sea Co-op vessels | Seatruck | 11.9 m, recovery vessel and boom deployment |
| | Seatruck | 6.1 m, back-up recovery vessel |
| | Jet Boat | 7.9 m, transportation to and from site, and standby vessel |
| Canmar Vessels | Barge | 15.2 m, base of operations, storage of recovered fluids |
| | Neakoolik | 14.9 m, oil discharge vessel |

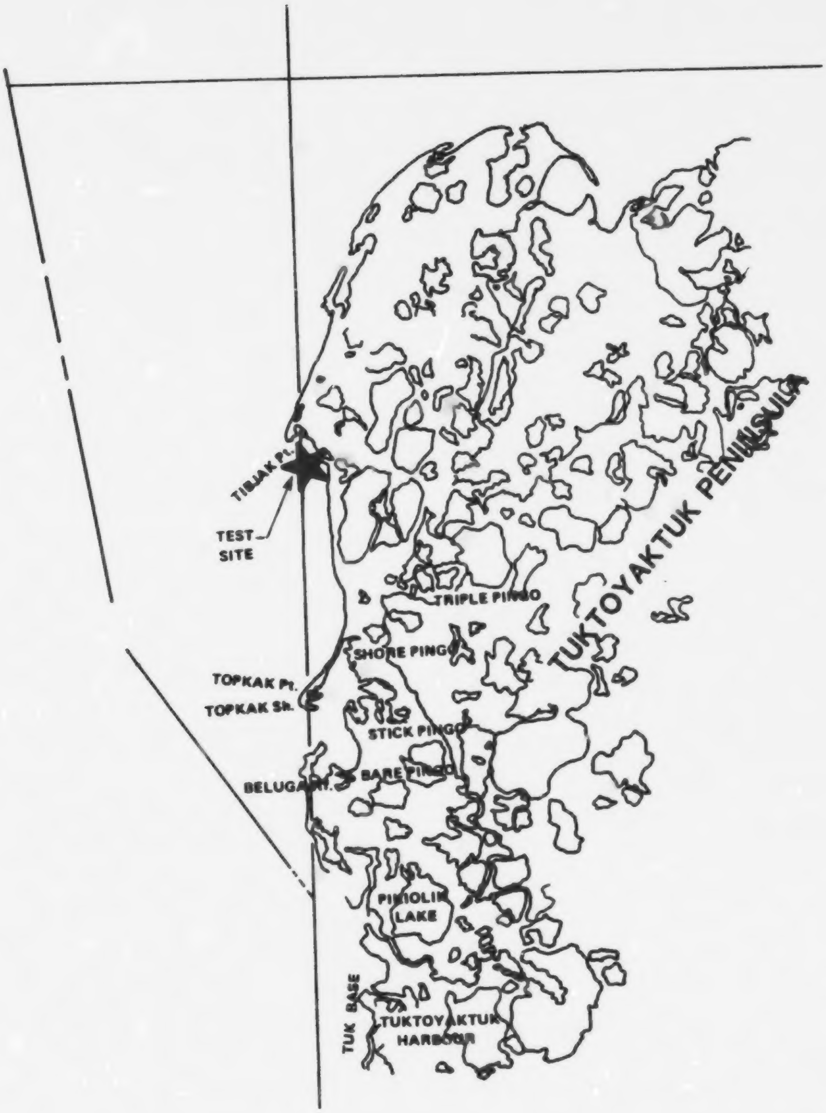
TIBJAK Pt.
TEST SITE
TRIPLE PINGO
SHORE PINGO
TOPKAK Pt.
TOPKAK Sh.
STICK PINGO
BELUGA Pt.
BARE PINGO
PINIOLIK LAKE
TUK BASE
TUKTOYAKTUK HARBOUR
TUKTOYAKTUK PENINSULA

FIGURE 3 TEST SITE

The following equipment preparations were made the day before the trials:

a) 20 drums (4,090 L) of canola oil loaded onto the Neakoolik;

b) 21 drums (4,250 L) of crude oil (Tarsiut Crude) loaded onto the barge;

c) the two skimmers (Clean Sweep and Arctic Skimmer) were lashed to the barge, trailing behind;

d) 91.4 cm navy boom and anchors were loaded onto workboats;

e) barge loaded with one collapsible porta-tank, required hosing, open top drums, miscellaneous equipment including sorbents and a Morris MI-30 skimmer;

f) 90.7 kg anchor set at test site by Neakoolik, to be used to anchor barge/skimming system.

## Experimental Procedure

The following summarizes the sequence of activities on September 9 and 10, the trial days:

82.09.09 1100: Neakoolik leaves Tuk base towing barge and skimmers.

1400: Equipment arrives at site, barge anchored, skimmers positioned, boom deployed to form a V-section in front of each skimmer, boom anchored. Back-up boom anchored downwind of barge. Sorbent boom tied to aft end of each skimmer (Figures 4 and 5 show the test configuration).

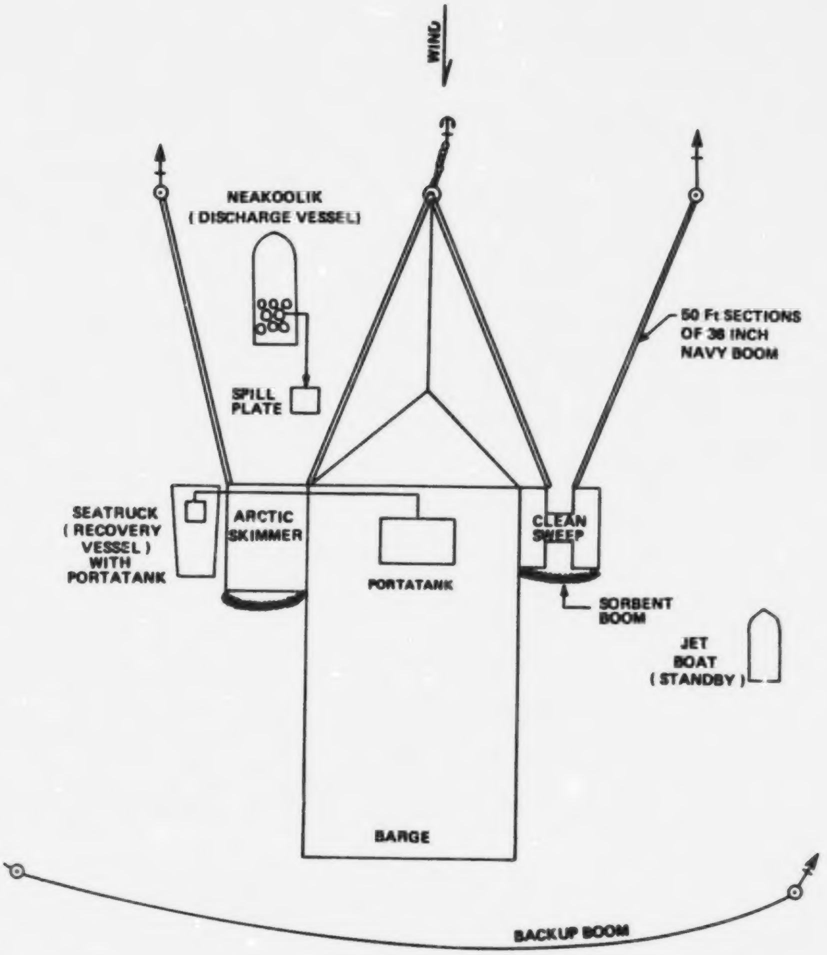
WIND
NEAKOOLIK
(DISCHARGE VESSEL)
50 Ft SECTIONS OF 36 INCH NAVY BOOM
SPILL PLATE
SEATRUCK (RECOVERY VESSEL) WITH PORTATANK
ARCTIC SKIMMER
PORTATANK
CLEAN SWEEP
SORBENT BOOM
JET BOAT (STANDBY)
BARGE
BACKUP BOOM

FIGURE 4 TEST CONFIGURATION

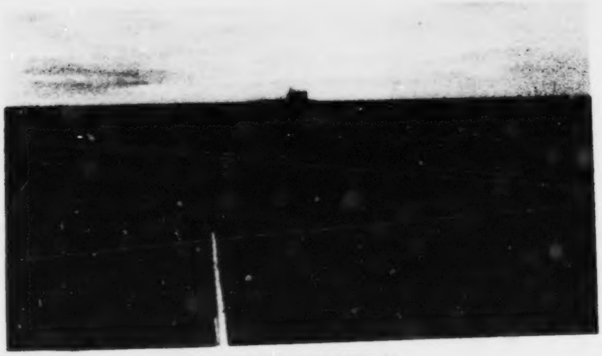

FIGURE 5 TEST CONFIGURATION

1815: Dry run of experimental procedure: pumping water from discharge vessel, run through of collection and sampling procedure.

1850: Began discharging canola oil in front of Arctic skimmer using SLURP skimmer as spill plate to reduce mixing (Figures 6 and 7). (Oil discharged at an average rate of 123 L/min.).

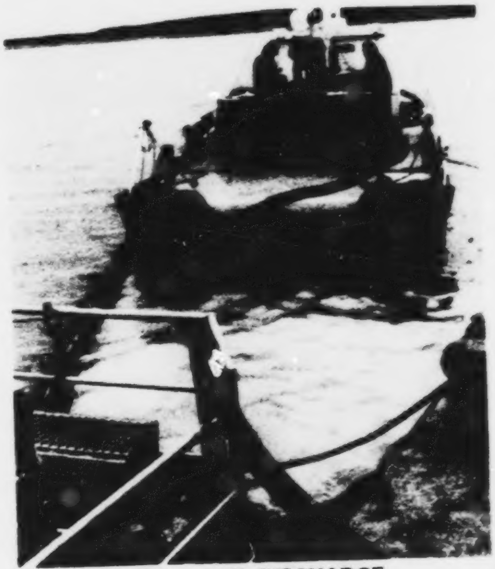

FIGURE 6 OIL DISCHARGE

FIGURE 7 OIL DISCHARGE

1850: Began recovering oil using Arctic skimmer. Recovered oil pumped into porta-tanks on Seatruck and barge (Figure 8). Samples of recovered oil taken intermittently.

1915: Discharge of canola oil completed.

2050: Recovery of canola by Arctic Skimmer completed. Equipment rearranged for canola test with Clean Sweep.

2145: Canola oil discharged from porta-tank (on barge) in front of Clean Sweep. Began Clean Sweep operations.

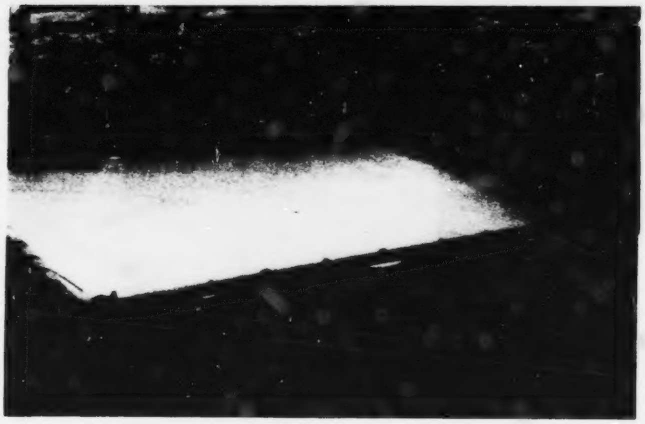

FIGURE 8 PORTATANK WITH RECOVERED CANOLA OIL (PHOTO)

2150: Tests halted due to excessive amounts of canola being entrained by the drum and resurfacing behind the skimmer (Figure 9). Discharge of canola halted, oil transferred to barge tanks.

(The planned test of the Clean Sweep with crude oil was cancelled due to its obviously poor performance with canola oil.)

2215: End of operations for the day. Barge left anchored overnight, personnel transported to Tuktoyaktuk via jet boat and Seatruck.

82.09.10 0830: Return to site. Preparations made for crude oil test with Arctic Skimmer.

0905: Began discharging crude oil (from barrels located on Neakoolik) in front of skimmer, again using the SLURP as a spill plate. Began recovery operations with Arctic Skimmer. Recovered oil pumped directly to barge tanks. Samples of recovered fluid taken periodically.

0955: Discharge of crude completed.

1200: Recovery operations completed. Final recovery of residual oil completed using sorbents. Final cleanup of booms, hull surfaces of each skimmer. Booms recovered.

1400: Barge, equipment towed back to Tuk base.

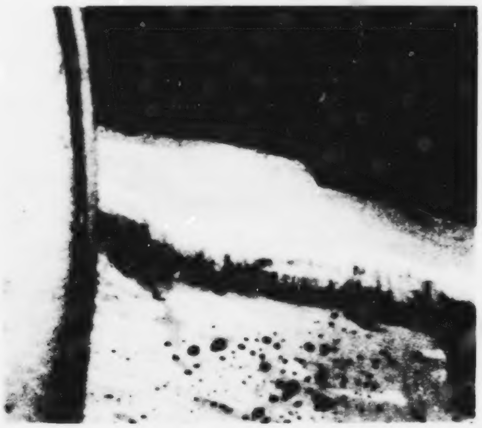

FIGURE 9 AFT END OF CLEAN SWEEP SHOWING ENTRAINED CANOLA OIL (PHOTO)

### Skimmer Variables

The Clean Sweep skimmer is very simple to operate, the only variable being the drum speed. For these tests, this was varied up to its maximum speed of 7 rpm.

The Arctic skimmer is much more complex, having several operating functions which contribute to overall skimmer performance. However, due to the limited amount of oil that was being spilled, it was not possible to properly investigate the performance as a function of the various operating variables. Therefore, these variables were set at predetermined values, considering the previous test results and the skimmer's operating manual. The following summarizes these variables:

Bow ramp - set at 35 cm below water level

Forward gill door - opened 10 cm

Aft gill door - opened 4 cm

Belt immersion - to middle of roller

Draft - skimmer ballasted to 60 cm draft

The belt speed was the only function which was varied for the trials. For the tests with canola oil, a constant belt speed was maintained. The belt speed was set at control setting "6" which corresponds to a speed of 0.75 m/s. For the tests with crude oil, the belt speed was varied over a range of values in order to assess the skimmer's performance as a function of this variable. The range of values considered were as follows:

| Speed Control Setting | Belt Speed (m/s) |
|---|---|
| 3 | 0.25 |
| 4 | 0.40 |
| 6 | 075 |

(Belt speeds estimated using observed values during the trials, and calibration table in skimmer operating manual.)

### Environmental Conditions

The days of the trials were generally overcast, with some broken cloud cover on each day. Information from Tuk base weather station indicates fairly stable wind conditions throughout the period of testing:

| | Wind Speed | | Direction[a] | |
|---|---|---|---|---|
| | Range | Mean | Range | Mean |
| 82.09.09 | 10 - 20 kt | 13 kt | 60° - 130° | 93° |
| 82.09.10 | 8 - 18 kt | 13 kt | 60° - 120° | 95° |

[a] Direction is degrees from true North.

The air temperature for the 2 days was fairly stable in the range of 4 to 9°C. Water temperature was measured at the site and was 4 to 5°C.

The wave height and period were visually estimated at the test site; the surface current was estimated using wood chips.

| | Wave Height | Wave Period | Surface Current |
|---|---|---|---|
| 82.09.09 | 15 - 45.7 cm | 1.1 - 1.3 s | 0.13 m/s |
| 82.09.10 | 30 cm | 1.2 s | 0.13 m/s |

### Oil Discharge Rates

The approximate discharge rates for the canola and crude are as follows:

Canola Oil: 3,680 L discharged over a period of 30 min, for an average rate of 123 L/min

Crude Oil: 2,500 L discharged over a period of 35 min, for an average rate of 71 L/min

### Sampling Procedures

Samples were taken periodically to measure the recovery rate and the properties of the recovered fluid. To measure the recovery rate, the skimmer discharge hose was placed in an opentopped drum. The volumetric flowrate was calculated using the time required for the discharge to fill one-third of the drum. At the same time, samples were taken from the flow of recovered fluid to be analyzed for water content. In addition, samples were taken of the two oils used (before discharge), and several samples were taken directly from the "Arctic Skimmer" recovery belt.

## RESULTS AND DISCUSSION

### Test Results

The following tables and accompanying graphs (Figures 10 and 11) summarize the recovery performance parameters which are defined by ASTM F631-80 (1980)

TABLE 1 TEST RESULTS OF THE ARCTIC SKIMMER - TEST WITH CANOLA OIL

| Time (From Start) | Fluid Recovery Rate | Oil Recovery Rate (ORR) | Oil Recovery Efficiency (ORE) |
|---|---|---|---|
| 5 min | 42.4 L/min | 29.7 L/min | 70.0% |
| 20 min | 93.1 L/min | 58.4 L/min | 62.7% |
| 60 min | 53.8 L/min | 28.2 L/min | 52.5% |

TABLE 2 RESULTS OF TESTS WITH CRUDE OIL

| Time (From Start) | Belt Speed | Fluid Recovery Rate | Oil Recovery Rate (ORR) | Oil Recovery Efficiency (ORE) |
|---|---|---|---|---|
| 40 min | 0.75 m/s | 48.6 L/min | 36.0 L/min | 74.0% |
| 60 min | 0.40 m/s | 28.4 L/min | 23.0 L/min | 81% |
| 75 min | 0.25 m/s | 10.2 L/min | 8.8 L/min | 85.9% |

ADDITIONAL OIL RECOVERY EFFICIENCY RESULTS:

| | |
|---|---|
| Clean Sweep recovering Canola Oil: | ORE = 50.0% |
| Arctic Skimmer belt sample, belt speed 6: | ORE = 59.0% |
| Arctic Skimmer belt sample, belt speed 4: | ORE = 70.8% |
| Arctic Skimmer belt sample, belt speed 3: | ORE = 80.0% |

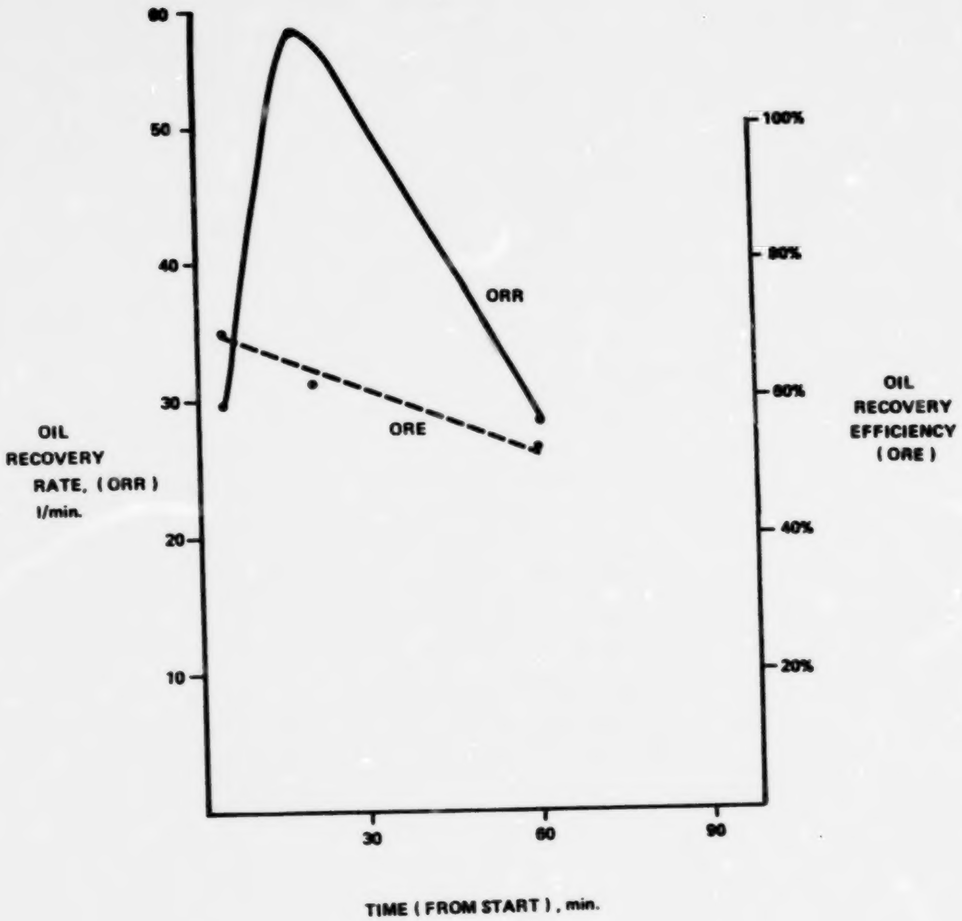

FIGURE 10 RESULTS OF CANOLA OIL TESTS USING ARCTIC SKIMMER

**Additional Observations**

The tests with canola oil revealed some important aspects of the Arctic Skimmer's performance characteristics. After a period of testing with the canola, the oil was observed to be quite viscous due to emulsification. This resulted in a decrease in the oil recovery efficiency (ORE) (see Figure 10) as an increased amount of water was picked up with the oil (water contained in the water-in-oil emulsion). In addition, the recovery rate (ORR) decreased from a peak value of 60 L/min to less than 30 L/min.

Towards the end of the canola oil testing, which had been conducted with a constant belt speed, the belt was slowed to approximately one-half the original speed (down to 0.4 m/s). The recovery rate at this speed was not measured, but was visually estimated to be substantially greater than the previously measured rates.

Two conclusions can be drawn from this test series: first, that the maximum recovery rate is greater for heavier oils than for light oils, and second, that the optimum belt speed is dependent on the oil viscosity - the belt speed for maximum recovery of heavier oils is slower than the optimum belt speed for lighter crudes. A more thorough study of this phenomenon, and the relationship of other operating variables, was not possible due to the limited amount of oil which could be spilled.

The belt speed was varied for the crude oil tests, and the results are indicative of what would be expected for a light crude oil. As shown in the summary plot (Figure 11), the recovery efficiency (ORE) decreases as the belt speed increases, but not enough to offset the rapidly increasing recovery rate (ORR). Unfortunately, the limiting conditions were not determined. However, extrapolating to the maximum belt speed of 1.7 m/s, one can estimate a minimum recovery efficiency of 70%, and a maximum recovery rate, for this oil, in the range of 40 to 50 L/min.

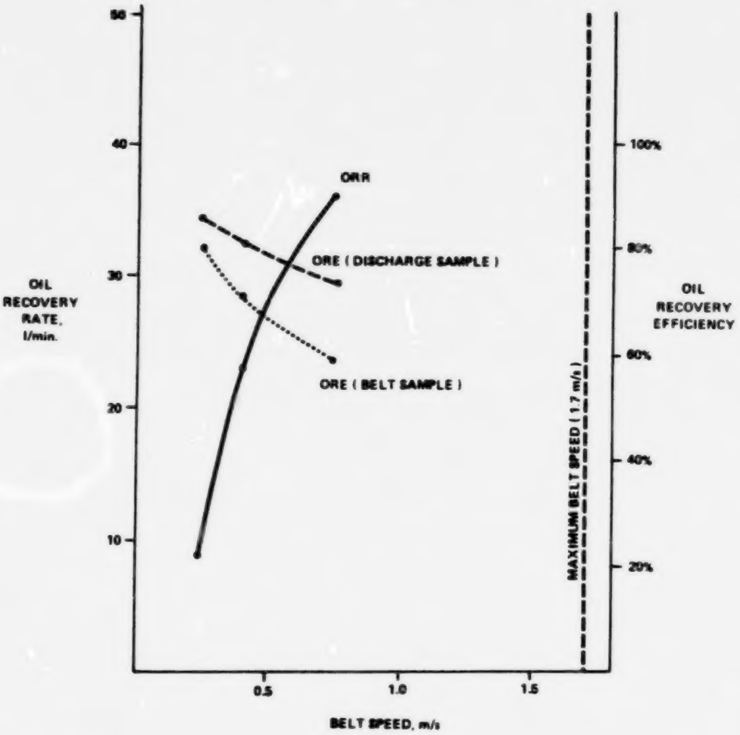

FIGURE 11 RESULTS OF CRUDE OIL TESTS

Referring to the same plot and comparing the recovery efficiencies from the belt and discharge samples, the curves are similar but separated by 5% to 15%. The difference is in the way the samples were taken: the discharge samples represent the fluid which was squeezed off the belt by the squeeze roller, while the belt sample was literally scraped off the recovery belt. Therefore, the belt sample has recovered water from the belt which would otherwise not be squeezed off. It appears that a relatively constant amount of water is contained by the belt, a problem which is probably due to using a sorptive belt which is not completely hydrophobic. A possible solution would be to ensure that the belt is thoroughly presoaked with oil before use.

### Comparison with Previous Tests

The Clean Sweep tests were very disappointing, especially when compared to previously successful trials by EPS and EPA at OHMSETT. However, the earlier tests were basically calm water tests and the fact that the results were not duplicated here is not that surprising considering the differences of the nearshore environment from that of a test tank.

Comparing the Arctic Skimmer with previous tests, one again finds a less than optimum performance by the skimmer. The highest observed recovery rate during this trial was approximately 60 L/min for canola oil, compared with a recovery rate of 330 L/min in OHMSETT testing. The following points are felt to be the major reasons for the decreased performance:

a) The main variable affecting recovery rate was found to be the viscosity of the oil. It appears that for an emulsified or otherwise heavier oil, the recovery rate would be much greater, and more comparable to the previously observed 330 L/min recovery rate.

b) The OHMSETT tests results noted that optimum performance was very dependent on the correct adjustment of several operating variables; setting of gill doors, bow ramp and belt angle may not have been optimized in these trials.

c) Factors relating to the age of the skimmer components may have contributed to decreased performance; for instance, the belt's sorptive capacity may have been reduced by the presence of tarry crude residues (from previous testing) on portions on the belt. This could be improved by simply replacing the belt and other worn components.

d) Finally, the obvious differences between field and test tank trials must be considered as a major factor in reduced skimmer performance.

In summary, these trials indicated that the two skimmers varied considerably in their ability to recover oil spilled at sea. The VEP "Arctic Skimmer" proved to be a reliable and efficient mechanism for collecting both canola and crude oil and, given the opportunity to adjust a variety of operating parameters during a more extended period of testing or operational use, the recovery rates and efficiencies described in the paper could, no doubt, be improved upon. The Lockheed skimmer, on the other hand, was ineffective at recovering the oil presented to it. As a result of these trials, Dome/Canmar is in the process of replacing the Lockheed Skimmer with the VEP skimmer as its primary method for recovering spilled oil at sea.

## CONCLUSIONS

1. The Lockheed Clean Sweep skimmer was found to be a poor oil recovery device in a nearshore environment. In fact, such a high proportion of the canola oil presented to it was entrained under the skimmer that the tests with it were terminated.

2. The VEP Arctic Skimmer was found to be a reliable oil recovery device, although its observed recovery rate was somewhat less than expected. Several factors may have contributed to this performance, including the small amount of oil used and the number of operating variables which could not be adjusted during the trial.

3. The fact that there are many operating variables on the Arctic Skimmer makes it a fairly complex device. Through experience, these variables would be optimized by an operator.

4. The small amount of oil may have contributed to the low recovery rate that was observed. One can only reliably state that the actual recovery rate for the Arctic Skimmer should be in the range of 60 to 330 L/min.

5. As far as recovery rate is concerned, the Arctic Skimmer shows much more promise for the recovery of viscous or emulsified oils. Further testing with emulsified crude oil would probably achieve a substantially greater recovery rate.

## ACKNOWLEDGEMENTS

This project was conducted by the Oil Spill Research Group of Dome Petroleum's Research, Marine Engineering and Design Department. Logistical support was provided by the Canmar Oil Spill Response Team (OSRT) utilizing Canmar and Beaufort Sea Co-op equipment. The assistance of the OSRT, and especially that of Mr. Dick Hanlon, Mr. John Latour and Mr. Seward Benoit, is gratefully acknowledged. This project was jointly funded by Esso Resources Canada Ltd., and Dome Petroleum Limited.

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# THE WEST NETTING SYSTEM FOR THE RECOVERY OF SEMI-SOLID OILS

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## SUMMARY

The use of a modified purse-seine netting system using a much finer net (only about 1-2 m wide) has been shown to be a novel technique for surrounding large areas of spilt oil at sea and for subsequently thickening the oil layer by slowly retrieving the net.

Various designs of net have been tested at sea; a design was obtained which is easy to construct and handle. The system has been shown to be capable of handling oils above about 10,000 cP at sea temperature. The release and recovery of 4 barrels of oil at sea was achieved with almost no loss of oil. The concept is seen to have great potential for the encircling and eventual recovery of large volumes of oil spilt at sea.

## INTRODUCTION

### General

Crude oil spilt at sea will usually spread rapidly and, in the course of a few hours, lose its lighter fractions. At the same time, most crude oils absorb seawater to form a water-in-oil emulsion. Some crude oils can absorb up to about 80% water, depending on the sea temperature and the degree of agitation of the sea surface. The resulting emulsions can be very viscous and not always amenable to the use of oil spill dispersants, especially if the viscosity of the mousse is above about 3000 cP at sea temperature.

Other crude oils, such as those obtained from the Beatrice oil field in the Moray Firth of Scotland, may be waxy in nature and cannot spread since the oil solidifies on contact with the sea. Such oils are normally pumped as warm fluids and may even have chemical wax modifiers added to improve their flow characteristics.

### BNOC Netting Work

The British National Oil Company developed a successful concept to trap small quantities of semi-solid oil in long, closed socks made of netting and held at the side of a small fishing vessel by means of a 4.6 m steel pole. The oil is directed by a partially open netting system into the sock where it is retained by the woven mesh of the net. The mesh allows air and water to pass through the net but is sufficiently fine to retain the oil. Quantities of up to about 0.91 to 1.8 tonnes can be held in this way; however, above about 0.91 tonne, the towing forces may cause the oil to be exuded through the net if the sea temperature is too high. Practical tests conducted by Warren Spring Laboratory showed that the Beatrice crude oil would probably exude from the net at sea temperatures above about 12.8°C. Nonetheless, the system was found to have some merit for handling small, nearshore spills of oil in colder seas.

### West Netting Concept

The use of a fine, woven net in the form of a sock led Mr. J. West, a Gardenstown fisherman, to suggest that the same kind of netting could be used to surround an oil spill. Techniques rather like those used in purse-seine netting, with the netting gradually being pulled in from the control vessel to thicken the depth of oil held in the net to several centimetres, would be used; thus, screw-pumps, disc skimmers or air transfer techniques (Springsweep) could be used to remove the oil. Unlike purse-seine netting, the oil recovery net does not need to have any great draught but does require an arrangement of floats and weights to hold the netting upright in the sea. Thus, the storage space in a purse-seine fishing boat could be adapted to hold an oil-retaining net which could be deployed from the stern of the vessel. However, a second boat having specialized oil pollution net recovery equipment and oil storage would be needed to recover oil.

The advantage of such an approach for dealing with thick oils is that nets can be held ready at any fishing port and rapidly deployed at an oil spill by fishing boats with local knowledge of the affected waters. The spilt oil cannot spread beyond the confines of the encircling net and the net plus oil may then be left to float under the influence of tides and currents until the specialized oil recovery vessel arrives on the scene. Long experience in catching fish with seine nets has shown that these nets, when surrounding fish, can be left several days in the sea without any risk of being washed ashore. The oil pollution netting was hardly affected by wind and, unlike impervious oil boom barriers, was not blown flat by strong winds.

This report describes the various experiments which have been conducted with nets to retain and recover viscous and semi-solid oils spilled at sea, in conjunction with the designer of the system and with Jackson Trawls Ltd. (now Jackson UK Ltd.) who now hold the patent rights.

### Potential of Seine Netting for Oil

Early experiments with nets held upright by nylon poles at frequent intervals and with floats placed mid-way on the net showed that the boom could be deployed with about half the net below the water and half above. This net was not significantly affected by wind. It was possible to demonstrate that the spreading forces of the oil and the inertia of the net in the water prevented the net from collapsing, thus removing the risk of the boom sagging and allowing oil to escape.

The normal purse-seine net used in the UK weighs some 16 tonnes and is about 700 m long by 180 m deep. It was then suggested that, if the net were only 2 m deep, it should be possible to deploy up to 90 times the length. However, such a relationship is meaningless as the oil boom netting is usually doubled for strength and is made from a much more closely woven nylon net than that used for fishing. Nevertheless, it was accepted that a fishing boat ought to be able to carry several kilometres of oil recovery net together with the support poles, weights and floats.

A boom 10 km long can be shown to encircle about 1000 tonnes of oil if the average thickness of the slick is only 0.1 mm.

## LABORATORY WORK

### Characteristics of the Net

The netting proposed by Mr. J. West (Figure 1) was very similar to that used to construct the BNOC Ltd. net sock. It was fabricated from 840 denier type 66 Nylon thread and had a bursting strength when fabricated of about 10 bar. The tensile strength was claimed to be 72.2 and 66.4 kg along the length and width of the woven cloth, respectively, measured using 25 mm wide test strips.

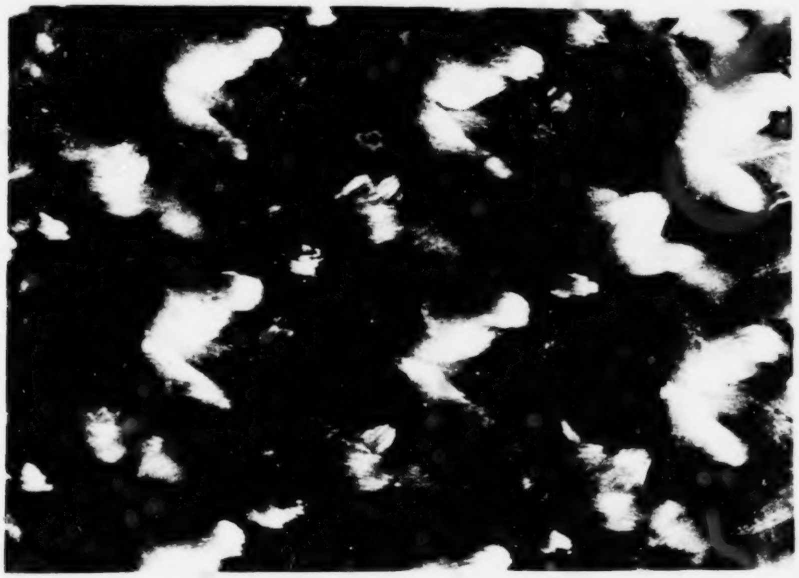

FIGURE 1 ENLARGEMENT OF NETTING (PORES 2-3 mm SIZE)

### Extrusion of Oil Under Load

During the development of the oil spill contingency plans for the Moray Firth area of Scotland, it had been established that up to about 2 tonnes of the high-wax, non-Newtonian, semi-solid Beatrice crude oil could be contained within the BNOC Ltd. net socks when deployed from fishing vessels in seas below temperatures of about 12.8°C when sweeping at speeds of about 2 knots. Laboratory tests substantiated by sea trials had shown that a force of greater than 5 g/cm$^2$ was required to extrude Beatrice crude oil through the oil recovery netting manufactured for Jackson Trawl Ltd. Results for extrusion of various oils through netting attached to one end of an 80 mm diameter cylinder of oil are shown in Figure 2. In these tests, different oils were placed in the cylinder to various depths; the quantity of oil which passed through the prewetted net was measured.

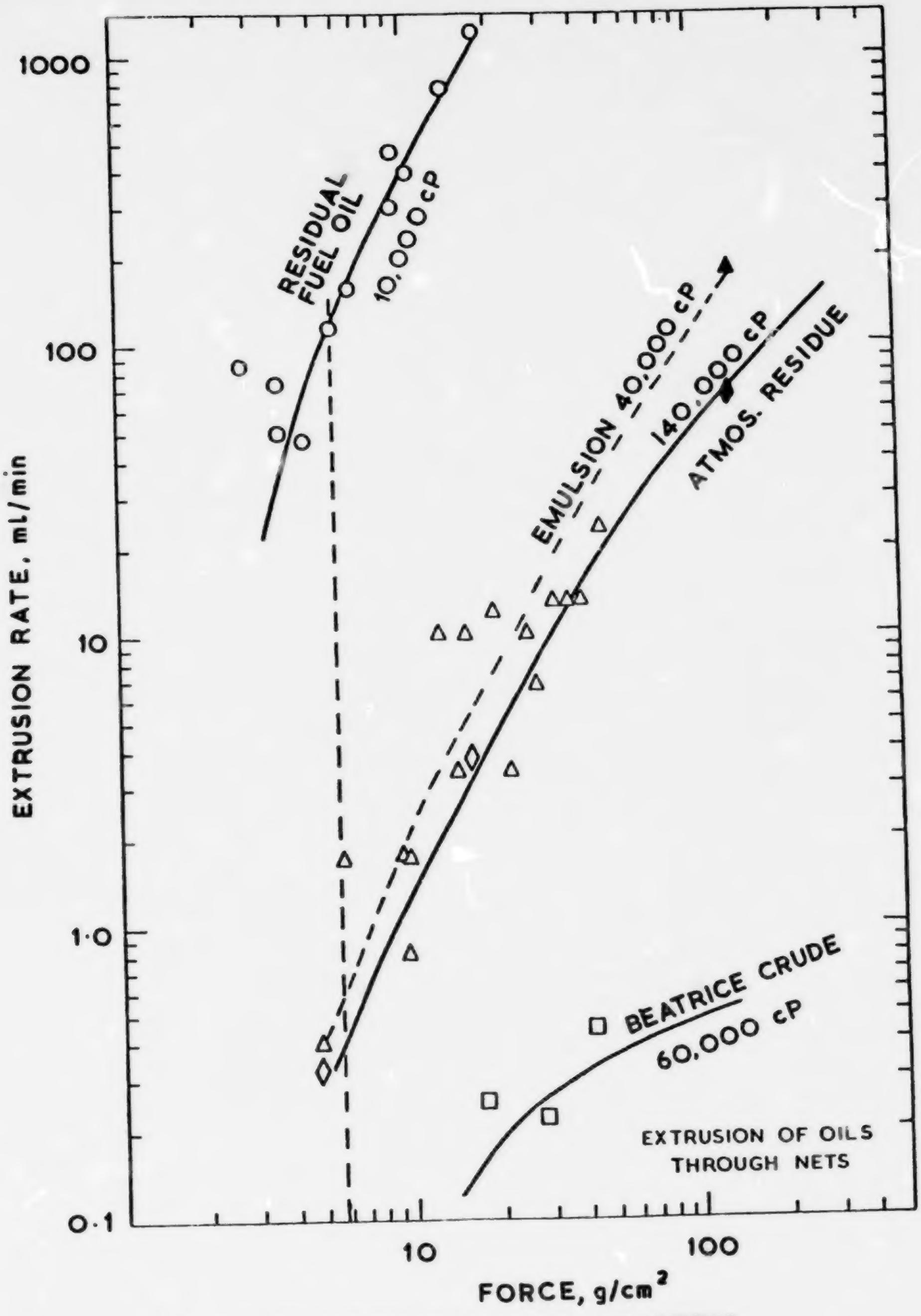

FIGURE 2 EXTRUSION OF VARIOUS OILS THROUGH NETTING

Although of value for assessing of the use of nets under tow, the figures obtained for the extrusion of oils of differing viscosity were unrelated to situations where the net boom was not being moved relative to the sea (i.e., where the boom floated with the sea current). Measurements were consequently made using a cylinder of netting held in a frame and floating in water. Quantities of oil were added to the cylinder until the pressure of the head of oil relative to that of the water was sufficient to cause oil to flow through the net. The viscosity of the oil at the prevailing temperature was then measured at different shear rates; the results are summarized in Table 1. As there are inertial effects due to wave motion in real conditions, the above figures need to be treated with caution. However, it is likely that oils of viscosity above about 10,000 cP would be retained by the oil boom nettings in moderately agitated seas. Such estimates of retention still have to be confirmed at sea, but the limited laboratory work reported here does show that the retention of oils by net, used as described, is possible even when the oil is moderately fluid.

TABLE 1 FLOW OF OIL THROUGH WEST OIL BOOM NETTING UNDER STATIC CONDITIONS

| Viscosity, cP (at 10 $s^{-1}$) | Leak Rate ($L/m^2 \cdot min$) | Oil Depth (mm) |
|---|---|---|
| 7000 | 0.03 | 400 |
| | 0.006 | 200 |
| 2300 | 0.91 | 90 |
| 1000 | 1.98 | 75 |
| 50 | 8.8 | 15 |

## SEA TESTS ON NETTING BOOMS

### Preliminary Tests

The first section of netting boom, constructed by Jackson Trawls Ltd., of Peterhead, was 60 m long and 1.5 m wide, with equal draught and freeboard (Figure 3). Main flotation and ballast were carried by vertical supports at 0.7 m intervals. The vertical supports were joined together by lines, set into the netting, at both top and bottom of the boom. Additional flotation was provided at the water line by small plastic fenders fixed to the netting. The nature of the netting can be judged from Figure 1. The small holes tend to close when the net is under tension.

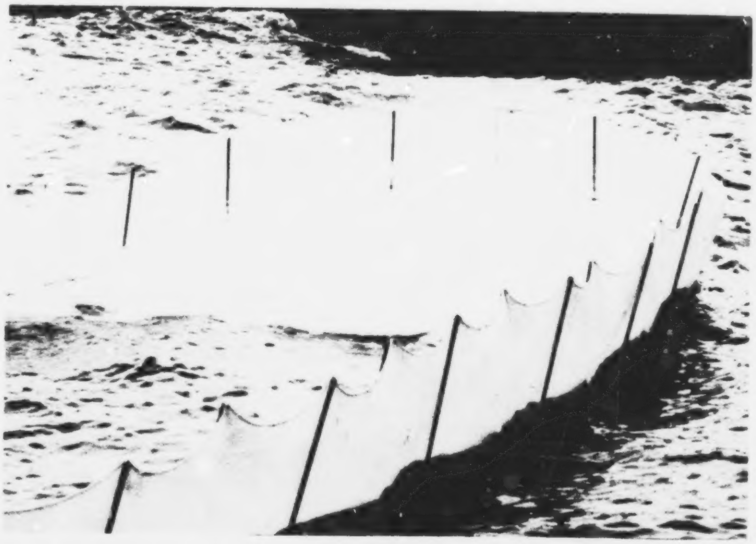

FIGURE 3 THE FIRST EXPERIMENTAL BOOM SECTION

The demonstration in Gardenstown Harbour, in November 1981, was timed at approximately high water; the synthetic, low-density foam placed in the boom deployed in a U-shape was seen to migrate to the closed end under the force of a 25 knot wind. The layer of foam reached a thickness of approximately 100 mm. When both ends of the boom were secured to the harbour wall, the opposite boom walls came together more slowly than expected. No loss of foam was evident from the 100-150 mm layer in the closed end.

A smaller piece of netting boom was deployed across the harbour mouth. This section was only about 10 m long and was not subjected to a foam retention test.

The boom appeared flexible, buoyant and easy to manoeuvre. There was evidence, even on the relatively short lengths deployed in the demonstration, that the 25 knot wind could flatten the boom wall. In the form deployed at Gardenstown, two men worked reasonably hard to recover the boom. One section at least had a tear below the water line after recovery.

Subsequent to the above successful test, the Marine Pollution Control Unit at the UK Department of Trade funded the production of two separate 200 m lengths of netting boom suitable for use in the open sea. A net hauling roller (Figure 4) was built for Jackson Trawls Ltd. and purchased by WSL.

### Modified Net Construction

The new boom system was about 2 m in height from the bottom of the skirt to the top of the freeboard. The net was stretched in the vertical plane by plastic rods, each fitted with a ballast weight, placed at intervals along its length. These rods in turn were spaced out by horizontal flotation tubes through the ends of which the rods passed. The flotation tubes were equidistant from the top and bottom of the resulting net barrier. The tubes were of two sizes: the larger was some 2.5 m long while the smaller was about 1 m. Both had a diameter of about 30 cm. Not all the spaces between the vertical rods were fitted with a flotation tube, however; but, in those cases where a flotation tube was absent, the horizontal distance between the verticals, equal to the length of a small flotation tube, was such that even if the pair of vertical tubes involved were to come together the resulting net sag between them would not be sufficient to produce zero freeboard at the mid-point.

### **First Open Sea Trial** (May 1982)

Weather conditions were very bad, with gale force winds, but it was agreed to sail with a 200 m length of netting boom stowed on the fishing vessel FLOWING TIDE; shelter was to be sought off Peterhead. The desired shelter was not found, the wind being in the North, with a strong swell and breaking seas running against a 1-2 knot northerly tidal stream. However, by afternoon, the wind had moderated to about Force 4 to 5 and the net was released.

In spite of its bulkiness, the new system was easy to handle; when the decision was taken to deploy the system at sea, the entire 200 m length was shot without incident in about 15 minutes by two men whose role was simply to guide the net over the transom of the ship.

Observations of the characteristics of this boom showed that it behaved very well and should be able to retain oil. However, the single layer of netting was torn in several places. It was agreed to reconstruct the system using a double layer of net but retaining the flotation system for trials involving the release of oil.

### **Second Open Sea Test** (July 1982)

A trial of a 200 m length of the modified netting system was conducted on 8 July 1982 in the Southern North Sea test area where the WSL Research Vessel SEASPRING was permitted to release oil. The weather was fair and the wind was slight (Force 2-3). The test consisted of releasing the net using a Zodiac six-man rubber dinghy to pull the net away from the boat and then deploying the net in an arc of a circle until the free end floating in the water could be retrieved on board to close the loop. In practice, once about 5 m of net were put into the water there was sufficient water resistance to assist the deployment of the net over the side of the vessel. However, the net was discharged using the hydraulic roller assembly mainly to assist the crew and to obtain experience for the subsequent recovery of the net.

Since only four barrels of oil were to be discharged, the 200 m length deployed was then slowly returned on board using the hydraulic net rollers until only about 50 m remained. A 39,000 cP artificially prepared water-in-oil mousse was then released into the small area of sea encircled by the net and the system allowed to float for about 30 minutes to see if there was any tendency for oil to escape under or through the netting.

The Springsweep oil recovery skimmer was then located near the position where the net rose out of the water and left a gap along the side of the ship. The net was gradually hauled back on board and the oil recovery system was used to recover the mousse. When the net was pulled back on board, oil was lifted up with the net and fell back into the gap in the circle; however, by careful positioning of the skimmer head, it was possible to collect this oil and so prevent a significant loss. As the net came on board it was washed with a high-pressure cold water system which returned almost all the entrapped oil back into the sea. Almost all the oil put into the circle of netting was recovered; there was no discernible loss either under or through the net.

The conclusions for the second trial were that:

(a) The system would retain an oil of about 39,000 cP under the sea conditions prevailing.

(b) The horizontal floats, either those 2.5 m long or the smaller ones, 1.0 m long, were an encumbrance and probably unnecessary. It was agreed with the Marine Pollution Control Unit to redesign the buoyancy arrangements using conventional floats fixed midway on each nylon upright.

(c) The Springsweep oil recovery system could easily be deployed with a net system to successfully recover almost all the oil discharged.

(d) A 2 m wide net seemed unnecessarily wide for the quiet sea conditions encountered during the trial.

### Third Open Sea Trial (October 1982)

The netting system was modified for the third trial. It became apparent from the previous sea trial that the vertical poles did not tend to come together when oil was present; there was consequently no need to use a horizontal member to keep the poles separated.

Two different sizes of a small spherical or pear-shaped float, through which the upright pole passed, were used, with buoyancies of 7 and 12 kg, respectively. For convenience, the floats were arranged alternatively on either side of the net to facilitate storage.

The sea trial was conducted off Aberdeen from the BP vessel FASGADAIR in sea conditions associated with winds of Beaufort Force 3. Again, the launch was remarkably easy and was accomplished in about 5 minutes. The exercise of joining two separate lengths of boom together was also demonstrated. As no oil could be deployed, there was some tendency for sections of the boom to fold back on each other. However, there was no fouling of poles or floats, and the system easily separated when gentle towing forces were applied.

### The Hydraulic Roller

Fishing Hydraulics (Scotland) Ltd., in cooperation with Jackson Trawls Ltd., designed a special hydraulically driven roller (Figure 4). This unit, weighing approximately 500 kg, was designed to have a main roller 2 m long and 34 mm in diameter. At each end of the main roller, a second smaller stub roller about 0.5 m long was placed in contact with the main roller so as to grip the net between each small roller and the main roller. Both the main roller and the small roller at each end were driven independently from a hydraulic power pack supplying 50 L/min fluid at pressures of up to 120 bar. The supply of fluid was reversed to drive the system in the opposite direction. The stub end rollers were loaded against the main roller but they could be lifted off from the main roller by application of hydraulic pressure to a separate circuit. This facilitated the clearing of any twists which might develop in the net.

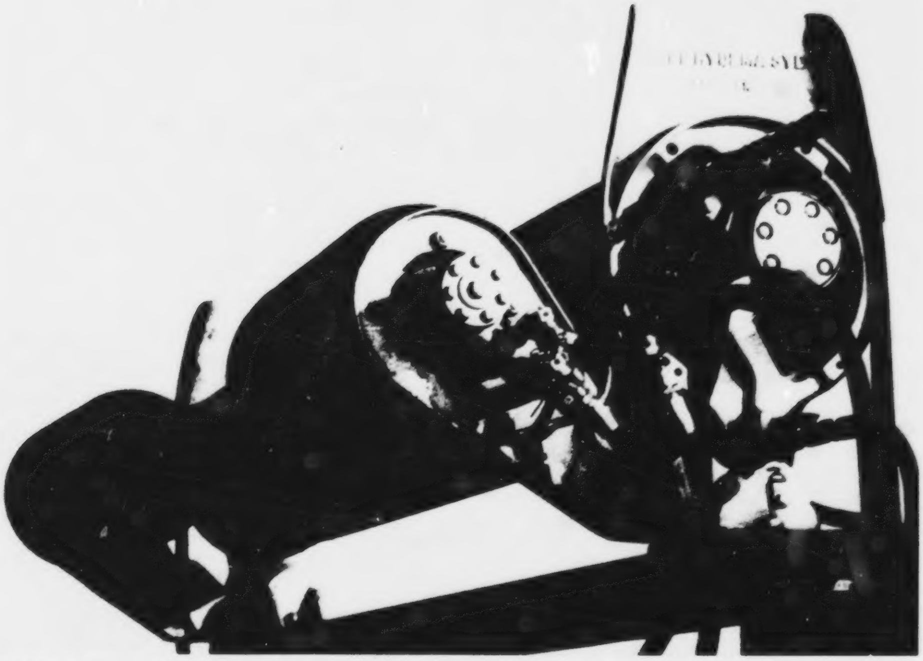

FIGURE 4 THE NET RECOVERY ROLLER

### CONCLUSIONS AND FUTURE WORK

The main conclusions which can be drawn from the work on purse-seine netting applied to oil recovery are as follows:

(a) the concept of employing purse-seine fishing techniques to surround and then concentrate the captured oil into a thick layer suitable for mechanical recovery is thought to have considerable potential for oils with viscosities above about 10,000 cP at sea temperature.

(b) Fishing vessels can carry and deploy several kilometres of net boom, enough to surround a large slick of oil. Fishing boats are experienced in the purse-seine netting technique, and several lengths of net can be assembled together at sea to surround even a very large oil spill (say, up to about 1000 tonnes).

(c) A dedicated vessel fitted with a purpose designed hydraulic roller is needed to recover the net. This vessel, if provided with tankage, could serve to hold the recovered oil.

(d) Once an area of oil has been surrounded, the net and the captured oil are affected almost entirely by sea current and will not be driven ashore by wind. Wind forces seem to have almost no effect due to the low wind resistance of the porous netting and the high inertial effect of the underwater section of the net acting like a sea-anchor. Thus, several recovery vessels should be able to remove the oil over a period of several days.

(e) Tests at sea have led to the buoyancy being redesigned and simplified. The oil-retaining tendency of the net has been demonstrated, albeit under relatively calm conditions.

(f) The system is very easy to deploy and recover. Cleaning of the net can be achieved by high-pressure water jets.

### Future Work

Jackson Trawl Ltd. has recently established a company, Jackson UK Ltd., to exploit the concept and to seek markets for the net boom. Two forms of a boom are envisaged, one 2 m wide, similar to that described in this report for at-sea use, and a second type 1 m wide designed for coastal water use. WSL hope to evaluate both types in further trials, particularly the concept of mooring the inshore boom as a deflection system to protect vital shore installations, such as power stations and cooling water inlets, from wind-driven oil pollution.

## ACKNOWLEDGEMENTS

The work described forms part of the program of research at the Warren Spring Laboratory funded by the Marine Pollution Control Unit (MPCU) of the Department of Trade. The authors wish to acknowledge the encouragement of Dr. D. Cormack of the MPCU, the enthusiasm and support of Mr. J. West, inventor of the system, and the assistance of Mr. A. Buchan of Jackson Trawls Ltd.

# TESTING OF OIL SKIMMERS OFFSHORE NORWAY - TESTING PROCEDURE AND RESULTS

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## SUMMARY

In Norway, three trials were undertaken in 1980, 1981 and 1982 with offshore mechanical equipment to collect oil. The 1980 trial was arranged by PFO; the two others were conducted by the Norwegian Operators Committee for Oil Spill Contingency (NOFO). In the two last tests, PFO also tested a new oil trawl developed after the 1980 trials.

In 1980, the scientific measurements were carried out by the Norwegian Hydrodynamic Laboratories (NHL). In the 1981 and 1982 trials, the Continental Shelf Institute performed the scientific measurements. These measurements covered environmental data, physical-chemical analysis of oil and water, and measurements to determine the efficiency and capacity of the equipment. The experiments were carried out in winds of Beaufort 3 to 5, with significant wave height (between 1.0 and 3.0 m). The towing velocity through the water was in the range 0.6 to 0.2 knots.

Only the first and last trials will be discussed here. The 1981 trial took place after a small amount of oil had been spilt; the trial was abandoned due to increasingly bad weather. As a result, the 1982 trial was arranged. The results of the trials showed oil recovery efficiencies between 10 and 70%. However, due to somewhat different test conditions, these numbers cannot directly be compared.

As part of the research carried out, we also measured the separation of oil and water in the tanks onboard the skimming vessels, both with and without addition of a de-emulsification agent. This showed that gravity separation in the tanks is possible without any special arrangements. The use of a de-emulsification agent, when added before a transfer pump, worked very well and separation was very good.

The viscosities of the emulsions used in the trials varied between 2,000 and 25,000 cSt. The emulsion used in the 1980 trial was made of lubricating oil, with water and an emulsion stabilizing agent added. The 1981 and 1982 trials used a topped crude from the Statfjord field offshore Norway.

## PURPOSE OF THE TRIALS

The purpose of the 1980 trial was somewhat different from that of the 1982 trial. In 1980, we wanted to establish if the then newly developed Norwegian skimmers had a potential to increase the recovery rate in an oil spill situation. The data obtained would be used to determine if further development would be possible with any of the equipment tested. In 1982, the prime aim for the NOFO was to establish knowledge of the capacity of the oil collecting system employed under realistic conditions offshore Norway. The aim of the PFO was to determine if an oil trawl, developed on the basis of the results of 1980 trials, could meet the specification set up for it.

## ORGANIZATION OF THE PAPER

This paper describes the scientific measurements done in the 1982 trials and developed on the basis of the experience gained in the 1980 trials (Lie et al., 1982). Also included is a description of the equipment tested. The results reported are based on reports by Langfeldt and Wold (1981) and Lie et al. (1982).

## SCIENTIFIC MEASUREMENTS

Data were collected on the following: sea state; wind velocity; air temperature; current and relative velocity of skimmer through the water; water temperature and salinity; volume measurements in tanks; and samples of released emulsion, emulsion ahead of skimmer, recovered emulsion and water with short intervals during each test, recovered emulsion, released water from holding tanks, and drained emulsion after each test. This extensive sampling program was set up to obtain information about the effect of the different operations on the chemical-physical properties of the emulsion. As a special task in the 1982 experiments, we also wanted to study the effect of adding an emulsion breaker. The sampling program is shown in Figure 1.

The chemical-physical properties of the oil and oil emulsion, and the effectiveness of the contingency action depend on the actual weather conditions. Environmental data collection is therefore a necessity during such operations.

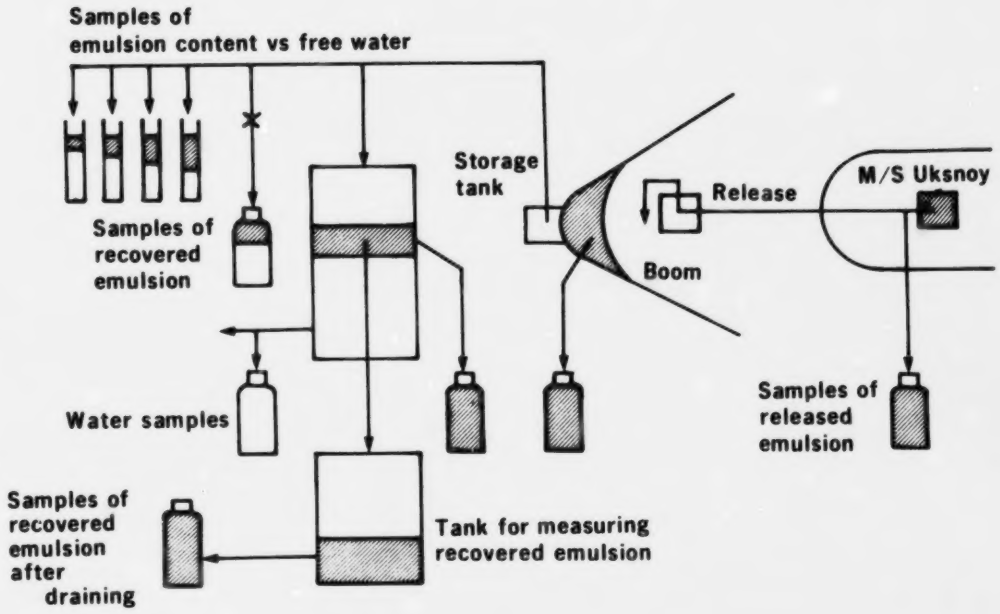
Samples of emulsion content vs free water
Storage tank
M/S Uksnoy
Release
Samples of recovered emulsion
Boom
Water samples
Samples of released emulsion
Samples of recovered emulsion after draining
Tank for measuring recovered emulsion

FIGURE 1 SET-UP FOR SAMPLE COLLECTION

### Environmental Measurements as Performed in 1982

**Waves.** The Datawell Waverider was used to measure the wave action. Measurements were radio-transmitted to the command vessel and registered on tape. Data were digitalized with a sampling interval of 0.5 s and analyzed on the analyzing program NEPTUN. We also made manual calculations of significant wave height based on registration on a recorded onboard. During the second cruise (April 1982), we also made calculations with the analyzing program MINI-NEPTUN.

**Meteorology.** Measurements of wind, air temperature, air pressure from the equipment onboard and from a handheld anemometer were also obtained.

**Sea Temperature.** The sea temperature was measured at the sea surface by obtaining a water sample and measuring its temperature on deck.

**Currents.** Relative currents between boom and water were measured with an Aanderaa current meter (RCM-4) at a depth of 5 m. The current meter was tied to a surface buoy which was attached to a boom. The purpose of these measurements was to measure the relative velocity between the boom and the water (Figure 2). The results from the current measurements were transmitted to the command vessel by VHF. The data were presented as physical values on an ABC-80 data terminal onboard. The sea current velocities and directions were calculated as the total drift of the surface layer based on predetermined tidewater information and weather observations onboard.

During the 1982 trials, sea currents were measured using a UCM-2 meter at a depth of 2 m (Figure 3). The measurements were based on 60 observations at 3 s intervals. There were 12 minutes between each sampling period.

### Chemical Analyses as Performed in 1982

Oil samples were measured as follows:

Measurement of water content: Method IP/70/74 "Dean-Starke equipment"

Measurement of viscosity: Feranty rotational viscosimeter
Shear rate 1.1 $s^{-1}$
Temperature: 3 samples at 20°C
4 samples at 8°C

Measurement of pour point: Method IP 15/67.

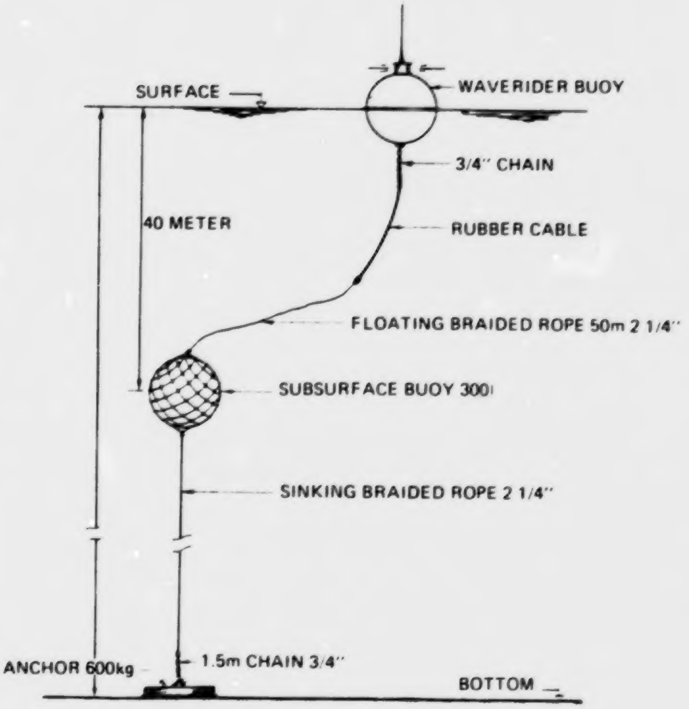
SURFACE
WAVERIDER BUOY
3/4" CHAIN
40 METER
RUBBER CABLE
FLOATING BRAIDED ROPE 50m 2 1/4"
SUBSURFACE BUOY 300l
SINKING BRAIDED ROPE 2 1/4"
ANCHOR 600kg
1.5m CHAIN 3/4"
BOTTOM

FIGURE 2 THE MOORING RIG FOR WAVE MEASUREMENTS

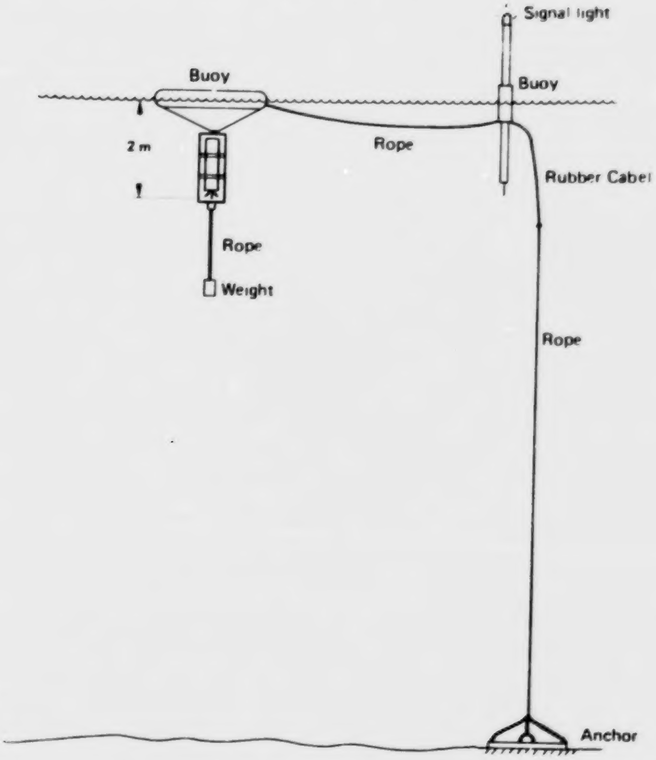
Signal light
Buoy
Buoy
2 m
Rope
Rubber Cabel
Rope
Weight
Rope
Anchor

FIGURE 3 THE MOORING RIG FOR THE CURRENT MEASUREMENTS

The water content was assumed to vary from release to collection. Therefore, we had to sample the oil emulsion at different stages through the operation (see Figure 1). The calculations of efficiency were undertaken because this variation in water content is related to waterfree oil.

Water samples were analyzed as follows: to calculate the loss of oil as a function of dispersion, water was sampled at several positions behind the boom during these operations. Samples were extracted with DCM which was then removed in the laboratory by evaporation in a Buchi rotavapor. The extracts was transferred to small sample receptacles and analyzed on GC and GC/MS.

GC conditions:
Gas chromatograph: HP-5730 A
Column: 30 m x 0.3 mm i.d. fused silica
Split injection: split ratio = 1:3
Carrier gas: $H_2$, 3 mL/min
Temp. progr. oil samples: -20 to 260°C 4 C°/min
Temp. progr. water samples: 40 to 260°C 4 C°/min

GC/MS conditions:
Gas chromatograph: Varian 3700
Column: 30 m x 0.25 mm i.d.
Temp. prog.: 80-260°C, 4 C°/min
Carrier gas: He, 2-3 mL/min
Splitless injection

The column was linked with a glass connection from the gas chromatograph to the mass spectrometer

Mass spec.: VG micromas 70-70
Electron energy: 70 eV
Scanning mode: TIC
Data collection: VG datasystem 20-35

### Efficiency as Measured in 1982

The efficiency was measured as follows:

a) with a Besto-Bell flow meter mounted on the pipeline between the skimmer and the main tank (Nilsen and Grønli, 1981; Nilsen and Nøsen, 1982);

b) in a 1 $m^3$ test tank which was filled at regular intervals by leading the flow from the pipeline directly into the tank;

c) by taking out 1-litre samples from the pipeline through two taps mounted on the top and two taps mounted on the underside of the pipeline;

d) by measuring the total amount of oil and water in the main tank of the boat. These measurements were carried out both with an Aanderaa WLR-5 pressure meter and by measuring the depth of the liquid in the tank.

## DESCRIPTION OF THE EQUIPMENT TESTED

The equipment tested is shown in Table 1 and in Figures 4 to 10.

## TESTING CONDITIONS

Table 2 gives a short resume of the test parameters.

## TEST SET-UP

The tests were performed using fishing and supply vessels. The test set-up in 1980 is shown in Figures 11, 12 and 13, and the one used in 1982 is shown in Figures 14 and 15. The method employed to use the skimmers should be evident from the earlier figures. We must, however, point out that in the 1980 test, the skimmer developed by Framnaes Mek. Vaerksted was held by a hydraulic crane inside the same booms as were used for the UNOCO system (see Figure 4).

In the 1982 test, two different FRAMO-skimmers were tested: the ACW400 and the Arctic. They were both held at the universal joint (Figure 10) by a hydraulic arm from the skimming vessel. The Arctic skimmer has a longer arm and more buoyancy than the ACW400. When testing the FRAMO skimmer, the boom was deployed in a double "U" configuration, as indicated on the top of Figure 15.

TABLE 1 EQUIPMENT TESTED

| Makers Name | Type of Equipment | Figure No | Tested |
|---|---|---|---|
| UNOCO | Single boat skimming system. Oil enters through six holes in the ship side | 4 and 5 | 20 and 29 June 1980 |
| Framnaes Mek. Vaerksted | Single boat skimming system. Oil picked up by weir skimmer | 4 and 6 | 20 and 29 June 1980 |
| Romsdals Fiskevegnfabrikk | Closed oil trawl with weir skimmer | 7 | 20 and 28 June 1980 |
| Fiskeredskap | Open oil trawl with weir skimmer | 8 | 21 and 28 June 1980 |
| Romsdals Fiskevegnfabrikk and Fiskeredskap | Newly developed open oil trawl with weir skimmer | 9 | 27 April 1982 |
| FRAMO | Combined weir and disc skimmer | 10 | 27 April 1982 |

The booms used were of the types NOFI XF-11 and NOAS KL-80, both manufactured in Norway.

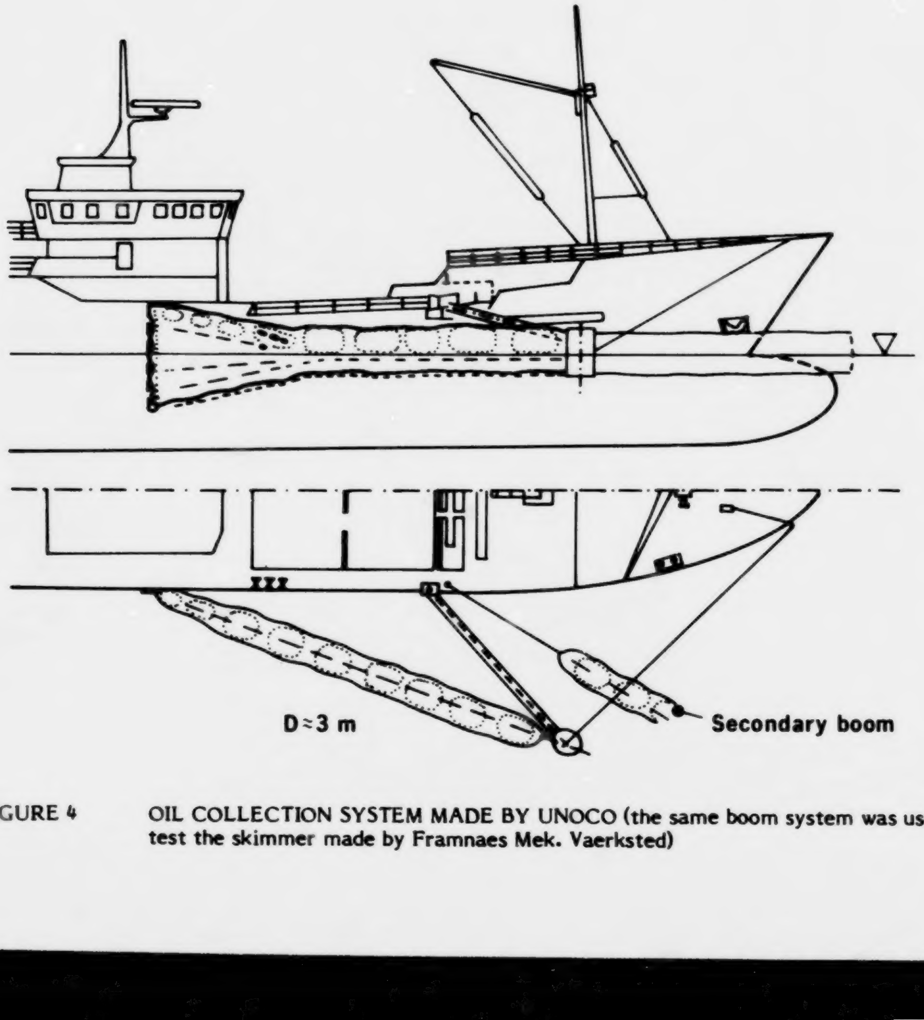

FIGURE 4 OIL COLLECTION SYSTEM MADE BY UNOCO (the same boom system was used to test the skimmer made by Framnaes Mek. Vaerksted)

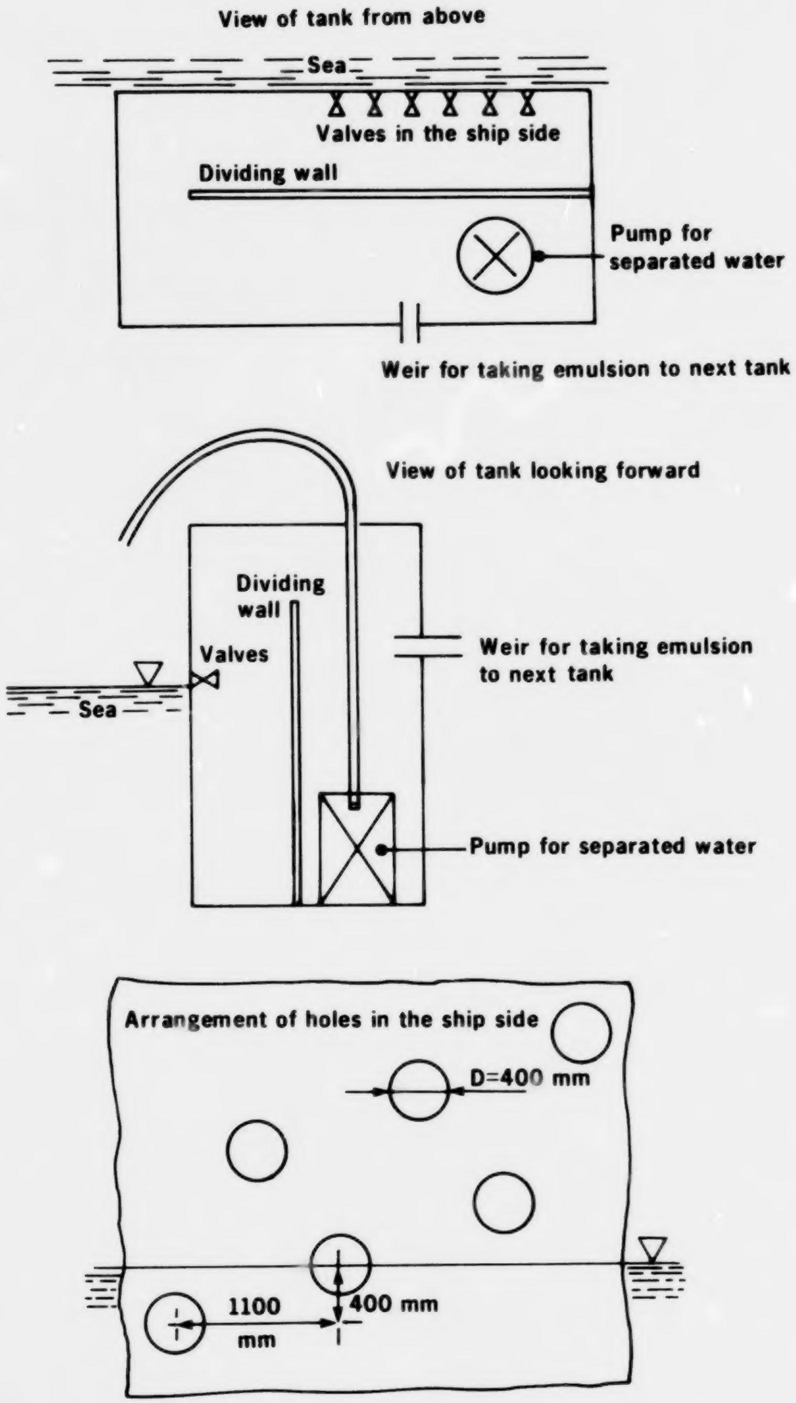
View of tank from above
Sea
Valves in the ship side
Dividing wall
Pump for separated water
Weir for taking emulsion to next tank
View of tank looking forward
Dividing wall
Valves
Sea
Weir for taking emulsion to next tank
Pump for separated water
Arrangement of holes in the ship side
D=400 mm
1100 mm
400 mm

FIGURE 5 ARRANGEMENT IN WING TANK FOR UNOCO'S SYSTEM

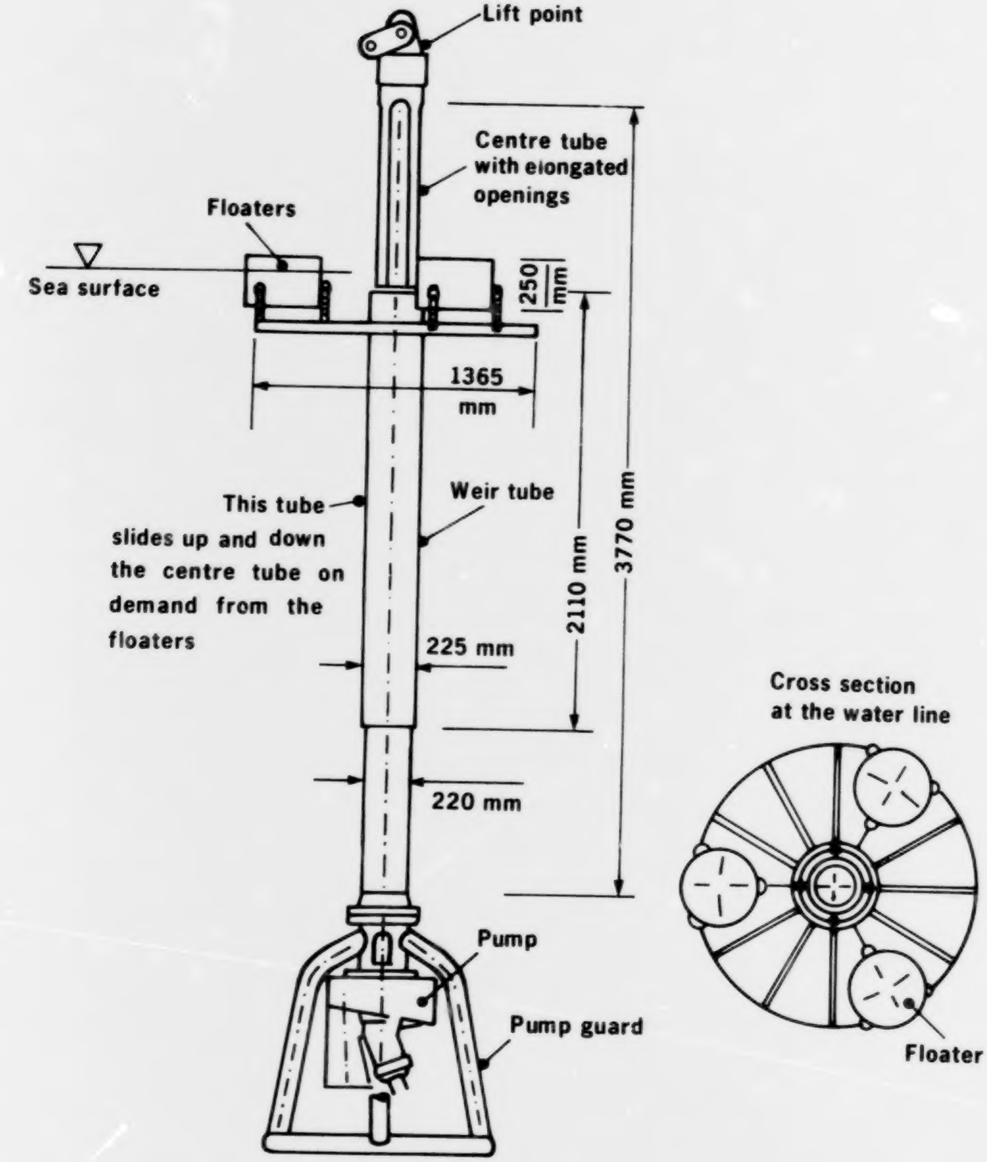
Lift point
Centre tube with elongated openings
Floaters
Sea surface
250 mm
1365 mm
This tube slides up and down the centre tube on demand from the floaters
Weir tube
2110 mm
3770 mm
225 mm
220 mm
Cross section at the water line
Pump
Pump guard
Floater

FIGURE 6 FRAMNAES MEK. VAERKSTED'S SKIMMER (measures in mm)

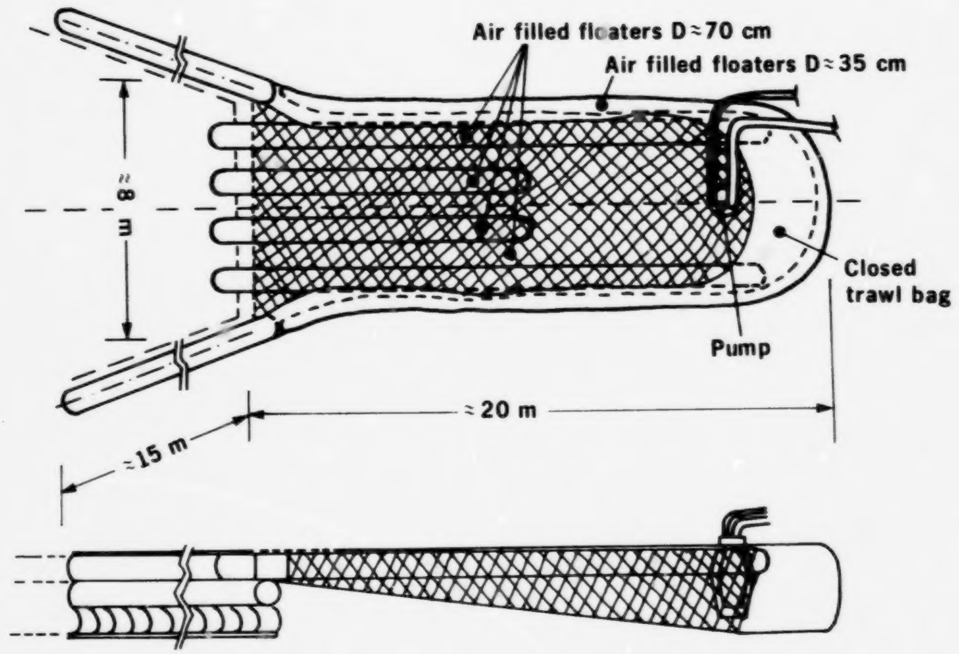
Air filled floaters D≈70 cm
Air filled floaters D≈35 cm
≈ 8 m
Closed trawl bag
Pump
≈ 20 m
≈15 m

FIGURE 7 ROMSDALS FISKEVEGNFABRIKK'S OIL TRAWL

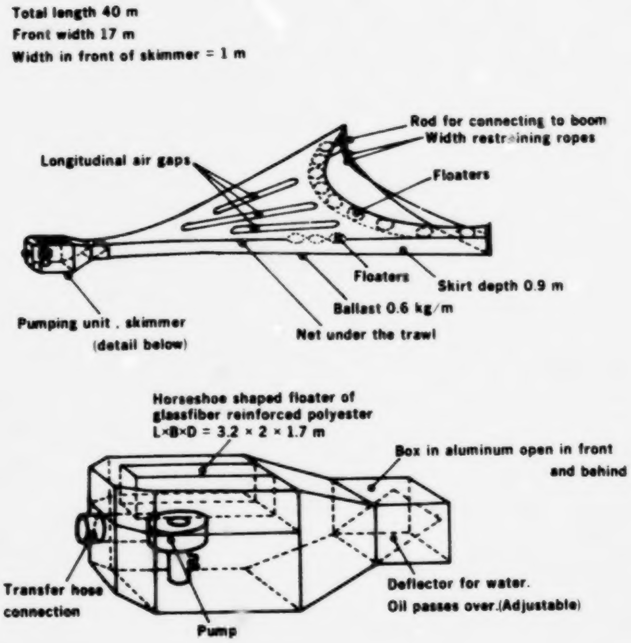
Total length 40 m
Front width 17 m
Width in front of skimmer = 1 m
Rod for connecting to boom
Width restraining ropes
Longitudinal air gaps
Floaters
Floaters
Skirt depth 0.9 m
Ballast 0.6 kg/m
Pumping unit , skimmer (detail below)
Net under the trawl
Horseshoe shaped floater of glassfiber reinforced polyester L×B×D = 3.2 × 2 × 1.7 m
Box in aluminum open in front and behind
Transfer hose connection
Deflector for water. Oil passes over.(Adjustable)
Pump

FIGURE 8 A/S FISKEREDSKAP'S OIL TRAWL

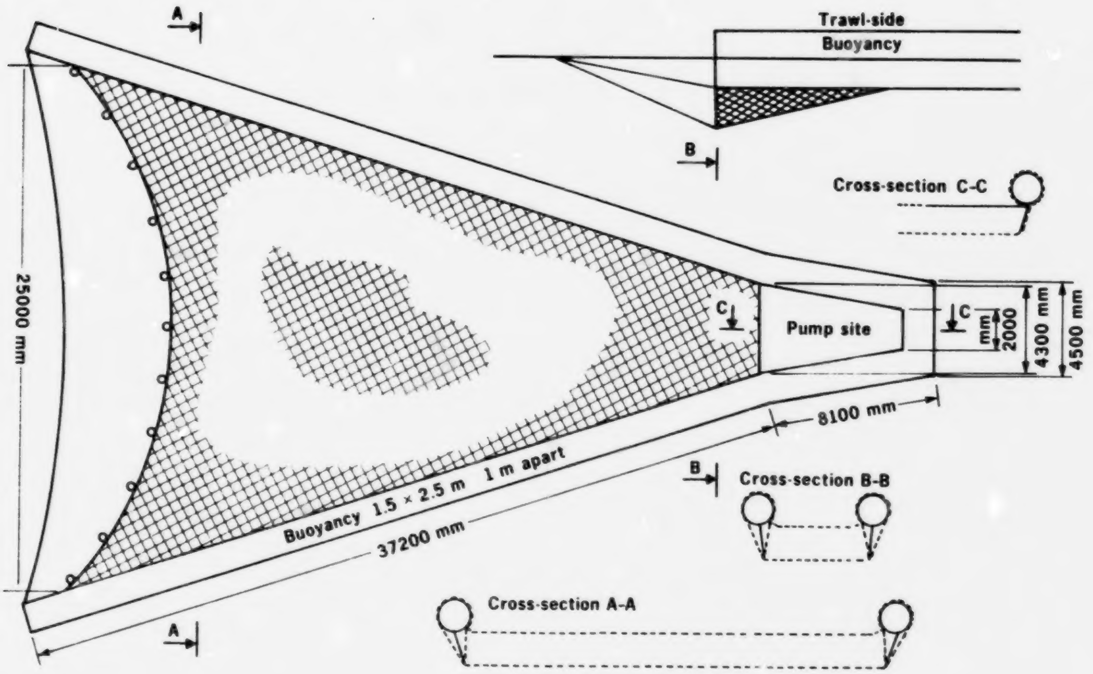
A
Trawl-side
Buoyancy
B
Cross-section C-C
25000 mm
C
Pump site
C
2000 mm
4300 mm
4500 mm
8100 mm
B
Cross-section B-B
Buoyancy 1.5 × 2.5 m 1 m apart
37200 mm
Cross-section A-A
A

FIGURE 9 NEWLY DEVELOPED OIL TRAWL

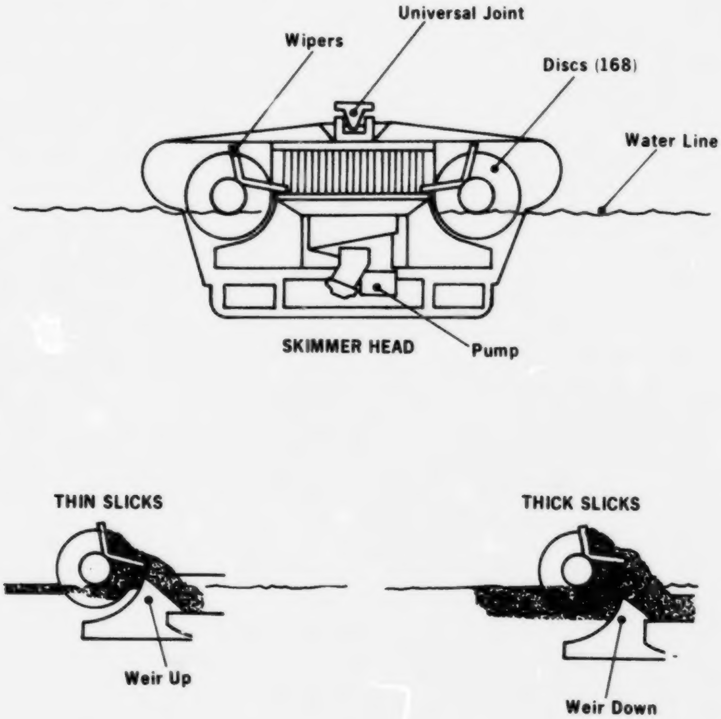
Universal Joint
Wipers
Discs (168)
Water Line
SKIMMER HEAD
Pump
THIN SLICKS
THICK SLICKS
Weir Up
Weir Down

FIGURE 10 FRAMO SKIMMER - OPERATING PRINCIPLES

TABLE 2 TEST PARAMETERS

| | 1a | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Significant wave height (m) | 2.6 | 1.9 | 2.7 | 1.7 | 2.5 | 1.3 | 2.2 | 1.4 | 1.3 | 1.4 |
| Average wave period (s) | 8.0 | 5.0 | 8.5 | 4.8 | 7.0 | 4.4 | 8.2 | 6.3 | 6.6 | 7.0 |
| Type of seaway | Swell | Wind generated | Swell | Wind generated | Swell | Wind generated | Swell | Wind generated | Wind generated | Wind generated |
| Wind speed (m/s) | 4.3 | 9.6 | 4.5 | 9.6 | 5.2 | 8.2 | 2.8 | 11.0 | 6.0 | 10.0 |
| Release rate ($m^3/s$) (emulsion) | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 400 | 55 | 76 |
| Total release ($m^3$) (emulsion) | 30 | 19 | 20 | 30 | 30 | 30 | 30 | 200 | 81 | 150 |
| Viscosity (cSt) | 11,000 | 25,000 | 11,000 | 25,000 | 11,000 | 25,000 | 11,000 | 2,000 | 2,000 | 2,000 |
| Relative velocity (knots) | 0.8-2.0 | 0.8-1.3 | 0.7-1.6 | 0.7-1.3 | 1.4-2.0 | 1.2-1.4 | 1.0-1.6 | 0.8-2.0 | 0.8-2.0 | 0.8-2.0 |

a 1 = UNOCO (20 June 1980)
2 = UNOCO (June 1980)
3 = Framnaes Mek. Vaerksted (20 June 1980)
4 = Framnaes Mek. Vaerksted (29 June 1980)
5 = Romsdals Fiskevegnfabrikk (20 June 1980)
6 = Romsdals Fiskevegnfabrikk (28 June 1980)
7 = Fiskeredskap (21 June 1980)
8 = New oil trawl (27 April 1982)
9 = FRAMO ACW400 (27 April 1982)
10 = FRAMO Arctic (27 April 1982)

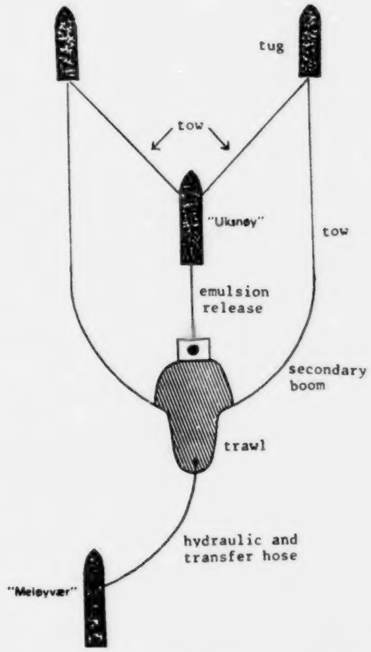

FIGURE 11 TESTING THE OIL TRAWL (20, 21 and 28 June 1980)

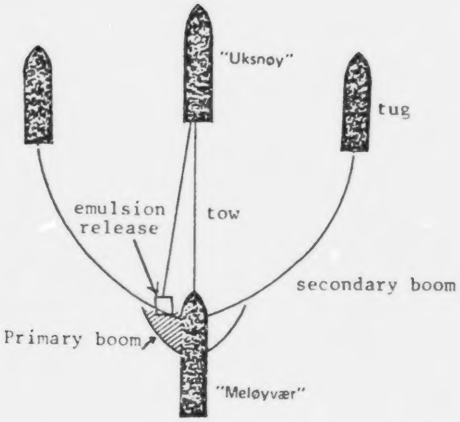
"Uksnøy"
tug
emulsion release
tow
secondary boom
Primary boom
"Meløyvær"

FIGURE 12 TESTING WITH BOOMS FROM THE SHIP SIDE (test with UNOCO's system, June 1980)

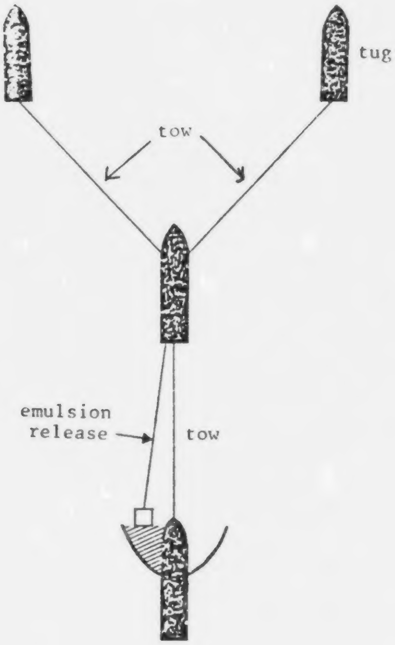
tug
tow
emulsion release
tow

FIGURE 13 TESTING WITH BOOMS FROM THE SHIP SIDE (29 June 1980)

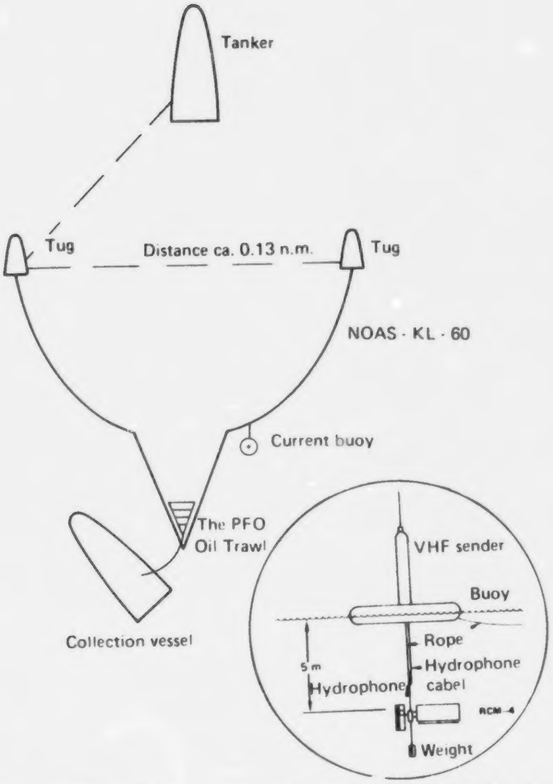
Tanker
Tug
Distance ca. 0.13 n.m.
Tug
NOAS - KL - 60
Current buoy
The PFO
Oil Trawl
Collection vessel
VHF sender
Buoy
Rope
5 m
Hydrophone
Hydrophone
cabel
RCM-4
Weight

FIGURE 14 THE EXPERIMENTAL ARRANGEMENT DURING THE OIL TRAWL TESTS 1982

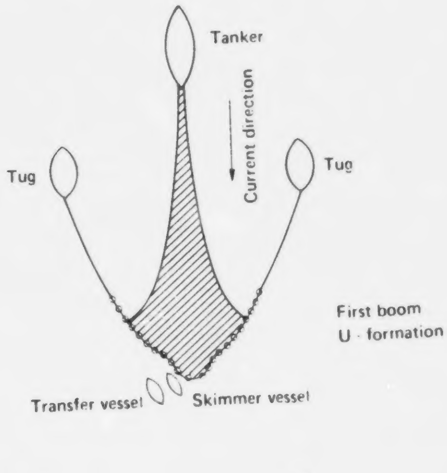
Tanker
Current direction
Tug
Tug
First boom
U - formation
Transfer vessel
Skimmer vessel
Second boom
J - formation

FIGURE 15 THE EXPERIMENTAL ARRANGEMENT DURING THE TEST IN 1982

## DISCUSSION AND RESULTS

### Efficiency

The measurements enable us to calculate the following values:

a) Amount of oil released, as a release ratio onboard the tanker and water content in the initial emulsion.

b) Amount of oil available, based on measurements of the thickness and the area of oil emulsion inside the boom system, and the water content of this emulsion. In most cases, the amount of oil available will be the same as the amount released. If there is a difference, it is because the released oil did not hit into the boom.

c) Amount of oil collected, based on measurements in the test tank, on the pipeline, and in the main tank, as a percent of the total amount of liquid, released oil, and available amount of oil.

d) Lost oil, calculated as released oil versus collected oil.

To get comparable values, the effectiveness calculations are related to waterfree oil or emulsion with the same water content.

Test results are listed in Table 3. The following equations are used in this presentation of the results:

$$\text{Total recovery capacity} = \frac{\text{Total volume collected (emulsion and water)}}{\text{time}}$$

$$\text{\% recovered} = \frac{\text{volume oil recovered}}{\text{volume oil released}}$$

$$\text{\% emulsion in total recovered volume} = \frac{\text{volume emulsion collected}}{\text{volume emulsion collected + volume free water collected}}$$

When taking the measurements to calculate the figures, we have to keep in mind that there will be a period only in the middle of the test that can be considered steady state. At the start and the end of a test, there will be periods of build-up and down. Some of the calculations may thus also be done for this steady state period. This is especially important if the steady state period is short, as it was in all tests except test No. 10 with the FRAMO Arctic skimmer. Where numbers are available, we have calculated figures for both the entire period and the steady state period.

TABLE 3 TEST RESULTS

| | 1[a] | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Percent recovered | 42 | 72 | 70 | 60 | 49 | 73 | 78 | 60 | 13 | 13 |
| Total recovery capacity ($m^3/h$) | | | | | | | | | | |
| whole period | 142 | - | 218 | - | - | 316 | 158 | 210 | 100 | 100 |
| steady state period | 215 | - | 223 | - | - | 311 | 161 | - | - | - |
| Percent emulsion in total recovered volume | | | | | | | | | | |
| whole period | 23 | - | 24 | 35 | 8 | 10 | 29 | 15 | 10 | 10 |
| steady state period | 38 | - | 31 | 46 | 11 | 16 | 42 | 50 | 5 | 5 |
| best reading | | | | | | | | 85 | 70 | 70 |

[a] See Table 2 for the description of the test numbering.

When comparing capacities, it should be noted that the UNOCO and Framnaes Mek. Vaerksted skimmers (tests No. 1, 2, 3 and 4) only give half the capacity of a system in use. The reason for this is that both were on one side of the vessel only. In actual use when installed on a vessel, the boom and skimming devices will be installed on both sides of the vessel and thus double the capacity.

### Weathering of Oil

Table 4 shows the results from the analyses of oil weathering in 1981 and 1982. No such analysis was undertaken in 1980. The oil used during the 1982 trial did not form stable emulsions. This influences both the viscosity and pour point. The viscosity of the emulsion used in 1982 did not exceed 2,000 cSt, while the emulsion used in 1980 had viscosities as high as 25,000 cSt.

TABLE 4 OIL WEATHERING

| | Water Content (%) | | Viscosity (cSt) | | Pour Point (°C) | |
|---|---|---|---|---|---|---|
| Sample taken from | 1981 | 1982 | 1981 | 1982 | 1981 | 1982 |
| Before emulsification | 0.0 | - | 16.8 | - | -6 | - |
| Emulsion before release | 63.5 | 59.1 | 2,100.0 | 1,616.7 | - | +2 |
| Emulsion on sea | - | 67.9 | - | - | - | +3 |
| Emulsion from the hose | 74.0 | 65.2 | 46,800.0 | 1,730.0 | +20 | +6 |
| De-emulsified oil | 0.0 | 0.0 | 25.7 | - | - | - |

The gas chromatographic analyses of the 1982 oil do not indicate any significant changes in the composition of the oil from release to collection. This is as expected as the oil was topped before emulsification.

### Oil in Water

Table 5 shows the results from water analyses done in 1982. No similar analysis was done in 1982. It is important to note that these results cover only the amount of oil in solution or distributed as fine, dispersed oil droplets. The samples from the tank also contained oil droplets which surfaced as soon as the samples were taken and the turbulence in the sample was minimized. In the 1982 experiment, we found amounts of dispersed oil as high as 85 g/L. It is also important to note that the amount of oil in the water was quickly reduced as the boat reached the harbour and thereby lowered the turbulence in the tank. Water samples taken from the tank when the vessel was in the harbour had hydrocarbon contents as low as 13.9 ppm.

TABLE 5 WATER ANALYSES

| Samples taken from | | Hydrocarbon Content 1982 (ppm) |
|---|---|---|
| Behind the boom: | 0 m depth | 1.93 |
| | 1 m depth | 0.25 |
| | 5 m depth | 0.11 |
| The hose | | 1,034.53 |
| The tank | | 562.33 |

The amount of oil in the tank water is of interest because this water is pumped out when the tank is full. With the amounts of oil we found, it means that we pumped out again approximately 200 litres of the collected oil in 1982. (The hydrocarbon content of this water was 750 ppm.) These analyses told us that it is important to wait until the tank is full before pumping out water. The full tank has a stabilizing effect on the liquid, improving the separation of oil and water.

From the water samples taken behind the boom, we see that oil is dispersed as a result of the boom being hauled through the water. During field experiments with drifting oil slicks, concentrations above 300 ppb were rarely reached. Usually, the concentrations are less than 40-50 ppb. The samples in this experiment were taken approximately 100 m behind the boom.

### Lost Oil

During the 1982 trials, we measured the amount of oil particles in the water behind the boom. The measurements were carried out with a nephelometer (Nilsen and Nøsen, 1982). The results show that the amount of oil escaping under the system was higher during the test with the Arctic skimmer than during the test with the ACW400. This may be due to the operation of the boom system which may have caused differences in relative velocities between boom and water. The loss under the Oil Trawl was less than the loss from the booms. The highest loss from the Oil Trawl was coincident with the period of the smallest recovery rate. The amounts of oil found in the water behind the boom do not, however, indicate that considerable amounts of oil disappeared under the boom under the operating conditions of the systems. Visual observations indicate that breaking waves were the most significant reason for the escaping oil.

## CONCLUSIONS

Due to the differences in experimental conditions, it is difficult to rank the skimmers being tested. It is, however, possible to state that the new Oil Trawl, given the possibility to build up a thick oil layer, is able to recover a significant amount of the released oil (58% in this experiment) with high capacity. We don't know how the skimmers will act if they are given the same conditions.

These experiments have shown us that exercises like this are a valuable tool, both as a test of the systems and as training for the crew. Measurements of environmental conditions like wind, waves, temperature, currents, and relative velocities between boom and water, as well as physical/chemical analysis of oil and water, are necessary to understand the different processes which influence the operation. These kinds of measurements should also be done during operations in actual oil spill accidents.

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# THE USE OF HIGH-PRESSURE WATER FOR SPILL CONTAINMENT

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## INTRODUCTION

Early in 1979 (at the time of the KURDISTAN oil spill on Canada's east coast), the Environmental Protection Service (EPS) was approached by a Vancouver-area specialist in the application of high-pressure waterjet technology. Based on research and experiments over several years, he had concluded that the technology could be applied to control and move oil slicks considerably more effectively that was possible with conventional booms or other current techniques.

The basic approach was to use the effect of the jets to move the oil over the surface of the water instead of moving or stopping the underlying water and, in so doing, influencing the floating oil. Earlier work at the U.S. Environmental Protection Agency's (EPA) Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility at Leonardo, NJ, had demonstrated that airjets and low-pressure waterjets were able to move floating oil (Cohen, 1979; Smith, 1981). However, no information could be found on the use of high-pressure water for that purpose. EPS, very much aware of the limitations of existing technology in ice-infested Arctic waters and in wave conditions commonly experienced off Canadian coasts, decided to find out whether or not some of the problems could be overcome by using water at substantially higher pressure (an order of magnitude greater), and at a correspondingly lower volume.

## INVESTIGATIVE APPROACH

Preliminary discussions led to a formal proposal by Ocean Dynamics International Ltd. (ODI) of Langley, B.C., to design and build a prototype system. The president, Mr. D.M. Christie, described his conceptual approach to interested industry and government oil spill countermeasures specialists in December, 1981. The general concensus was that a small-scale test should be undertaken to compare the actual performance to that predicted for the setup chosen, and that the effect of waves should also be investigated.

### Concept Analysis

A simple, small-scale test was designed. It consisted of an array of three jets spaced along a fixed manifold that was to be mounted on floats and secured in a boomed-off channel alongside a barge. Wood chips were to be used to simulate oil, and pressures ranging from 5,516 to 13,790 kPa were to be available. An effective range of 23 m was predicted for the setup.

Specialists with hydrodynamic expertise were invited to critique the test design and the predictions made regarding performance. They included the U.S. members of the OHMSETT Interagency Technical Committee, the group that controls the operation of that facility. Their subsequent alternative offer to investigate the use of high-pressure waterjets on oil slicks in their tank as an OHMSETT-funded project was most welcome and was accepted without hesitation.

## OHMSETT TEST

A test protocol was developed by Mason and Hanger - Silas Mason Co., Inc., the operating contractor for the OHMSETT facility, in consultation with Mr. Christie. A 7-phased series of 32 test runs was planned for the purpose of qualitatively assessing the sensitivity of high-pressure waterjet barriers to changes in the following parameters:

a) jet height above the slick surface (10-150 cm);

b) jet flare angle (15°, 25° and 40°);

c) pressure (11,032-17,237 kPa or 1,600-2,500 psi);

d) flow rate (221-140 L/min or 57-36 US gpm);

e) current speed (0-5 knots);

f) wave characteristics (calm; short, low, regular; and 0.6 m harbour chop).

Most of the assessments were to be made on the basis of a direct confrontation between the jet effect and the oil. However, the plan did include a few runs to assess diversion capability. Time and cost constraints precluded a test program that would accurately establish the optimum combination of the several variables.

A design specification of the test installation was prepared by ODI in consultation with the OHMSETT test engineer. A 6.1 m wide channel was to be boomed off along one side of the tank. A three-jet manifold made up using 19 mm steel pipe was to be clamped to supports on the main towing bridge so that jet height could be varied. A pumping unit capable of producing at least 295 L/min at 27,579 kPa was specified.

The OHMSETT project report was still in preparation at the time this paper was written. The results described were derived from the OHMSETT draft overview report and from personal observations.

A trailer-mounted, diesel-driven Triplex pump of the type most commonly used by water-blasting contractors was rented. It was purported to have the required output capacity and was positioned on the main bridge as shown in Figure 1. The jet manifold and boomed-off channel are also shown. The only significant departure from the specification prepared by ODI was that pipe with an inside diameter of only 10 mm was used to make the manifold.

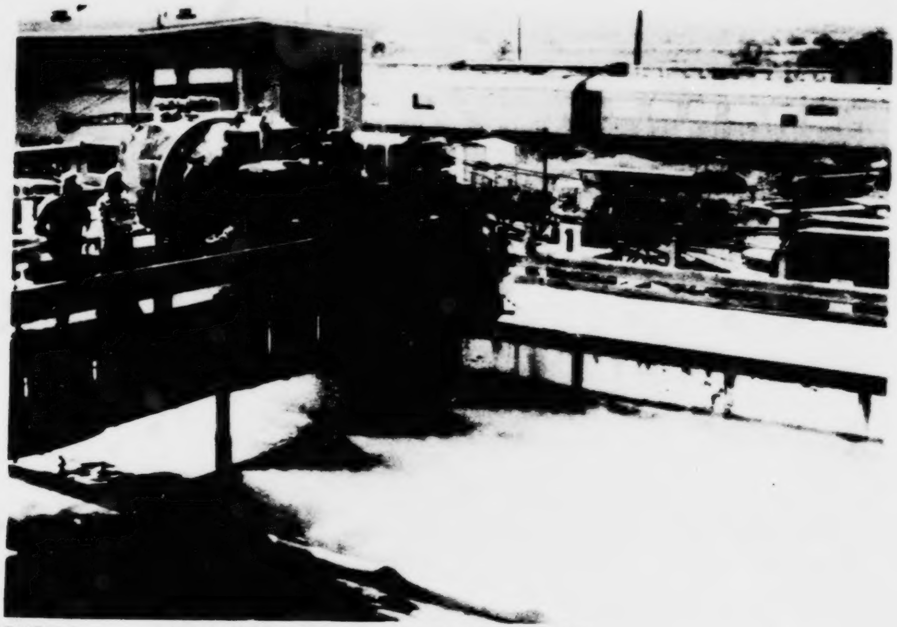

FIGURE 1 TEST ARRANGEMENT WITH SINGLE PUMP

It was soon found that the required flow and pressure combinations could not be developed and hence the jets could not perform as designed. Nevertheless, their ability to move oil was still quite impressive.

The procedure used to assess the result of a change of one of the variables was to lay a 2 mm slick of Circo X heavy oil within the channel. Then, the jets were turned on and the rate at which the oil moved down the tank was recorded, as was the distance at which movement essentially ceased.

Figure 2 shows the swept area extending 18 m or so beyond the auxiliary bridge, a total movement of approximately 38 m. The limit of oil movement for these runs ranged from 45 to 60 m, which was substantially more than the predicted 17 m. The time taken for the oil to be swept the first 7.6 m ranged from 10 to 38 seconds, which translates into average speeds of 20 to 76 cm/s or 0.4 to 1.5 knots. The time to reach 30.5 m ranged from 1 min 48 s to 3 min 49 s. The corresponding average speed of oil movement over the longer distance ranged from 13.3 to 28 cm/s or 0.25 to 0.5 knots.

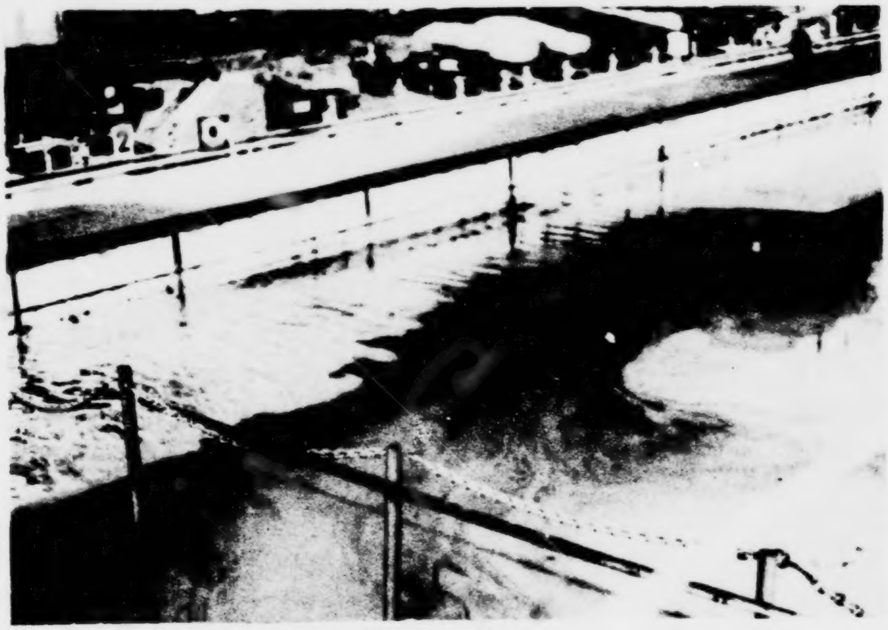

FIGURE 2 OIL MOVED APPROXIMATELY 38 m

To more closely achieve the desired jet flow rates, a second pump was placed on a truck and connected to the other end of the manifold. As shown in Figure 3, the number of jets was reduced to two and the width of the channel was reduced by about 1 m. The resulting interference between the boom and the end of the manifold raised the minimum height at which the jets could be set to about 280 mm.

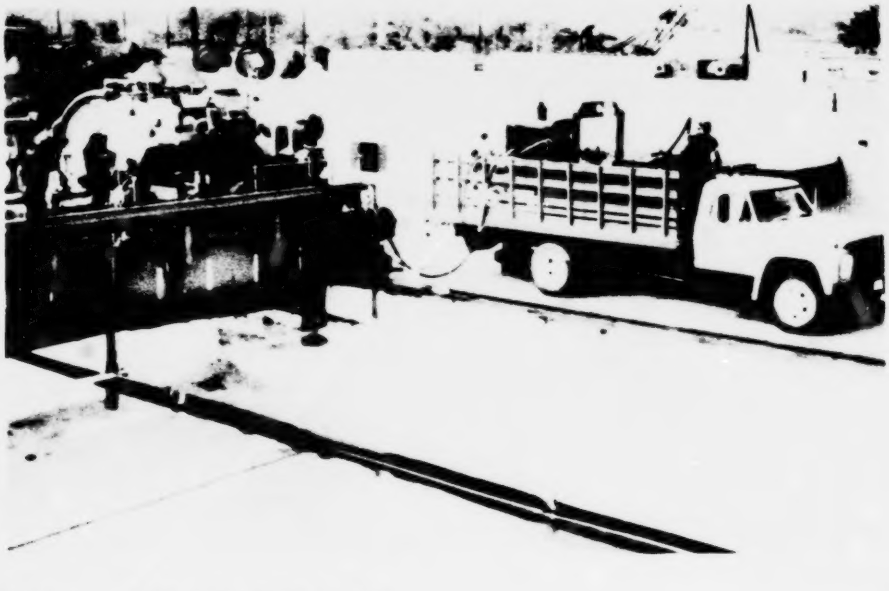

FIGURE 3 TWO-PUMP TEST SET-UP

The flow of air induced by the jets was such that a breeze could still be felt at the limit of the oil movement up to 60 m down the tank. A further indication of the large amount of air being drawn in was the presence of a waterspout behind and about midway between the jets at some settings.

To assess the ability of the jets to move oil against a current, the bridge was advanced at various speeds immediately after the jets were activated. The intent was to simulate moving oil encountering a fixed barrier. Over-running occurred at about 0.75 knots. Figure 4 was taken during one of these runs.

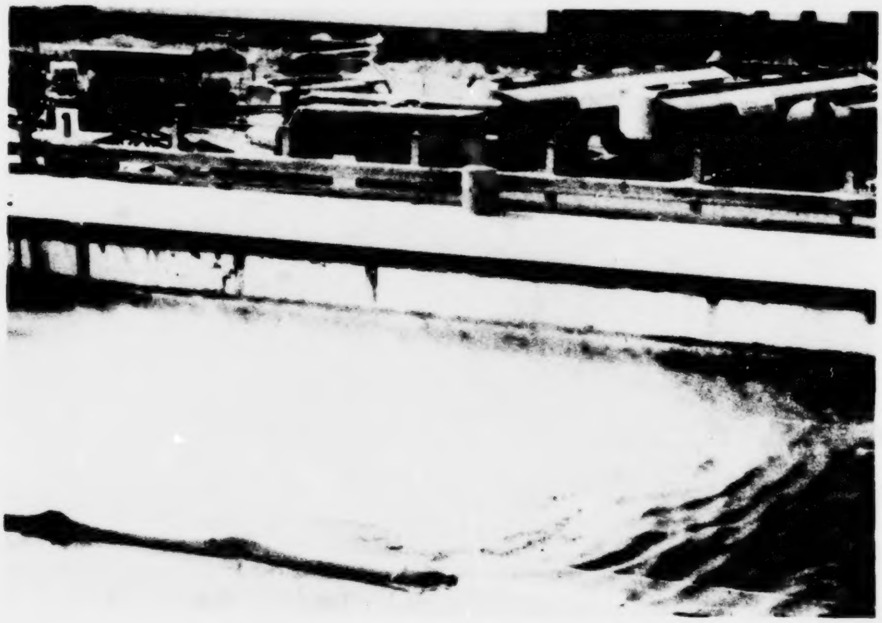

FIGURE 4 OIL BEING MOVED BY JET EFFECT

During the runs in wave conditions, the manifold had to be raised to about 1 m above the water to avoid wave contact and possible damage to the bridge structure. That was well above the optimum height: to partially compensate for the loss of efficiency, the jets were depressed about 10° below the horizontal. Two wave conditions were used; 0.4 m regular waves spaced 7 m apart, and the 0.6 m harbour chop. Over-running occurred at about the same speed and to the same extent in waves as in calm conditions. This was true even in the harbour chop. It has been well established that conventional barriers are unable to hold oil at any speed under those conditions. The jets impacting the face of each oncoming wave created small whitecaps of very brief duration, but did not noticeably flatten the waves or reduce their height. Although each wave briefly interrupted the jet effect on the oil, the resulting pulses appeared to move the oil as well as the steady flow had done under calm conditions.

As a final test, the two jets were directed at an angle of about 45° to the direction of travel as shown in Figure 5. This left a strip of oil along the tank wall that was not contacted, but the rest was swept cleanly across the tank at speeds of advance of up to 1 knot even though the jets were still positioned well above their most effective height.

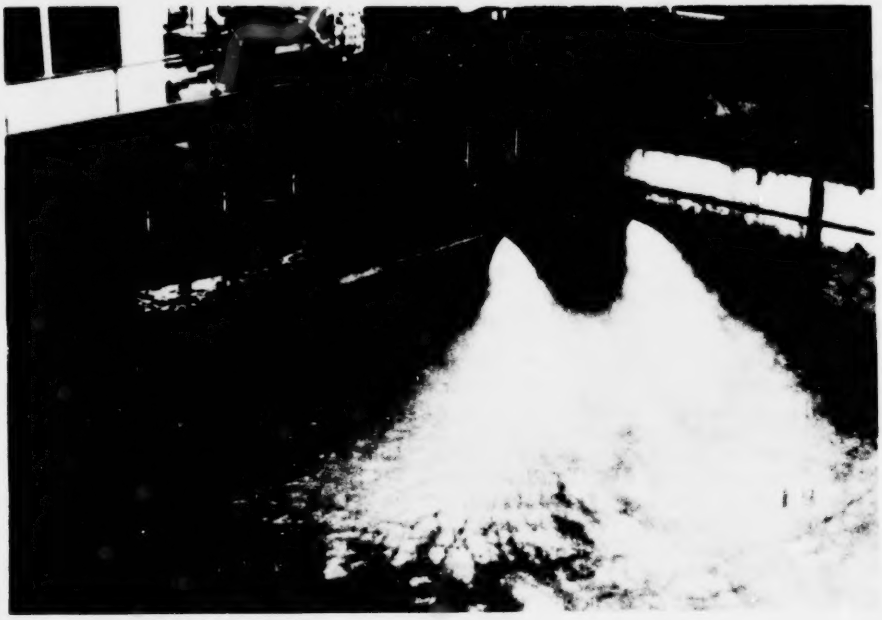

FIGURE 5 OIL DIVERSION TEST

## EXPERIMENTAL SYSTEM DESIGN

The OHMSETT tests clearly demonstrated that high-pressure water jets will effectively move oil on water even when power and orientation are less than ideal. Although the optimum values for the main parameters could not be precisely determined in the time available, they were quantified sufficiently for the design of an experimental barrier system. Accordingly, ODI was tasked to produce a specification for a diesel-driven power plant and two waterjet barriers, one for containing a slick and one for diverting or moving oil to a desired location.

### Pump Specification

From the OHMSETT results, it was deduced that the pump for an experimental system might have to be able to deliver up to 2,600 L/min at a pressure of 7,200 kPa to achieve optimum performance from a barrier approximately 50 m long. That was the length chosen as the minimum that would permit a reasonable assessment of the operational potential of high-pressure waterjet barriers. That output requires a 500 horsepower unit, and the horizontal triplex-plunger type was chosen on the basis of its established reputation. If so desired, a pump of that capability can also deliver 87 L/min at a pressure of 116,080 kPa, a feature that might well prove useful at a spill scene where cutting or cleaning operations are required.

An uprated 550 horsepower 8-cylinder G.M. Detroit diesel has been selected to drive the pump. It is equipped with spark arrestors, electric start, and an air-cooled exhaust system. The main pump, diesel engine, fuel tank, charging pump and the associated power take-offs and controls are mounted on a rugged steel skid that has oilfield-type rolled ends and lifting hooks. The assembly is 4,267 mm long, 2,134 mm wide, 1,676 mm high (14 ft x 7 ft x 5 1/2 ft), and weighs about 6,800 kg (15,000 lbs.). It can therefore be transported by road or Hercules aircraft and operated from the working deck of a Sealander-type vessel, a barge, a supply ship, or from shore.

### Barrier Specifications

The overall design objective is to create an experimental oil barrier by exploiting the ability of high-pressure waterjets to move oil. More specific objectives include:

a) minimum cost;

b) 100% effectiveness in currents up to 4 knots;

c) ready adaptability for operation at water temperatures as low as -2°C and air temperatures as low as -30°C;

d) comparable performance in seawater and freshwater;

e) ease of modification to improve performance or to explore new possibilities for use.

### Barrier Designs

Two waterjet barriers have been designed. One is intended for restraining floating oil and the other is for moving it. Both will have opposing pairs of jets arranged in series. Each pair will be mounted on a low, floating platform so that the jets are projected horizontally from origins not more than 30 cm above the surface of the water. One jet in each pair will act on the oil; the other will provide the counteracting force that will be adjusted as necessary to advance the barrier or to effect a retreat. A pair of light, flexible hoses supported by buoyancy collars will connect each pair of jets to the next pair of the series array. The jets will emit a flat spray pattern with uniform droplet distribution and tapered edges.

The oil-restraining barrier jets will be uniformly spaced, about 2.4 m apart initially, pending determination of the optimum spacing during trials. The 15 m supply/tether lines from the pump will also be supported by flotation collars and will connect to the barrier at its mid-point to form a "T" as depicted in Figure 6. The jets will be directed inwards about 30° towards that intersection and their patterns will overlap to provide a continuous barrier. This angling of the jets towards the middle of the barrier also makes it possible to position the barrier laterally by temporarily unbalancing the forces in the opposing arms of the "T". Using this capability in conjunction with the advance/retreat capability will enable the operator at the pump output controls to manoeuvre and shape the barrier without requiring the assistance of other watercraft.

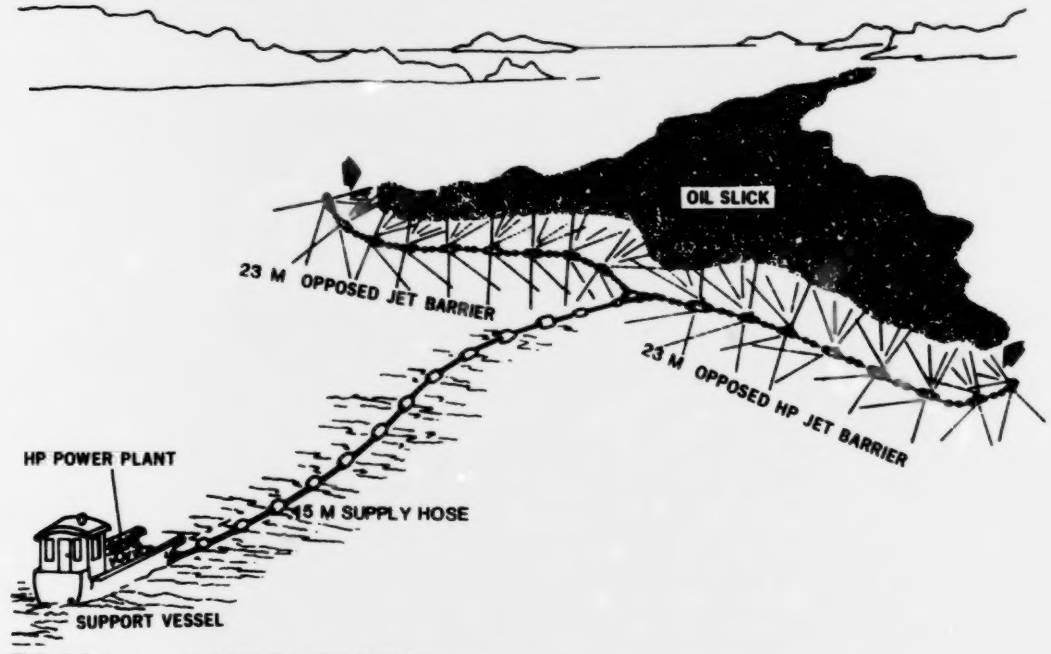

FIGURE 6 OPPOSED-JET BARRIER

The oil-moving barrier, which has been designed to divert oil or to convey it to a holding area, will be supplied/tethered from one end. Its jets will be spaced further apart at about 4.8 m; they will emit a narrower spray pattern, and they will be directed so that the centreline of each spray will be at an angle of about 45° towards the tethered end.

## EVALUATION PLAN

When this paper was written, a power package was ready for delivery to EPS and action had been initiated to have one of each type of barrier made up. Functional testing is scheduled to begin in the Vancouver area in July 1983. Public demonstrations (without oil) are planned once any "bugs" in the systems have been corrected. Quantified performance testing with oil at OHMSETT could follow by late September 1983, subject to the availability of that facility and the results of the initial functional tests. Other trials would follow until the potential for applying high-pressure waterjet technology to deal with spilled oil has been satisfactorily assessed. Operational evaluations by the Canadian Coast Guard or others would be included. Possible applications currently include:

a) containment for in situ burning with combustion enhancement achieved by the associated water injection and induced air supply;

b) sweeping oil from mud flats and marshes with minimal additional damage;

c) extricating oil from areas of broken ice;

d) conveying oil that is too viscous to pump.

## CONCLUSION

The results of the work to date continue to indicate that at least some of the major deficiencies in current spill countermeasures capability might be overcome using high-pressure waterjet technology.

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# DEVELOPMENT AND EVALUATION OF VISCOUS OIL RECOVERY EQUIPMENT

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## INTRODUCTION

Numerous oil pollution incidents have occurred in which bunker fuel oils have been spilt on the surface of the sea in low ambient temperatures and the equipment available was unable to effectively recover the resultant highly viscous oil and water-in-oil emulsions which formed.

In the United Kingdom, the BP Research Centre, working on an oil spill recovery equipment project, has developed new equipment for the recovery of highly viscous oils and water-in-oil emulsions. Prototype equipment employing arrays of rotating toothed discs and a screw pump has been constructed and has undergone evaluation trials. Emulsified F80 (3500 Redwood No. 1 seconds) fuel oil with an apparent viscosity of 400,000 centistokes at 2°C (shear rate 5 sec$^{-1}$) has been successfully recovered.

This paper summarizes the factors limiting the performance of various viscous oil recovery principles. The design of equipment incorporating the necessary requirements for effective viscous oil recovery is outlined. Development details are given, and results of evaluation trials are presented.

## PHYSICAL PROPERTIES OF FUEL OIL AND WATER-IN-OIL EMULSIONS

The mechanisms required for the recovery of viscous oil and water-in-oil emulsions relate to the physical properties of the oil (viscosity, specific gravity and pour point) and their effects. Heavy fuel oil is normally heated for tanker discharge. When spilt on the surface of the sea and subjected to low temperatures, its viscosity increases substantially, making pumping and other forms of handling increasingly difficult. Recovery efficiency is greatly reduced because the viscous oil does not readily flow towards the equipment or into the voids created by the skimming action.

The specific gravity of fuel oil is close to that of water; when the oil is subjected to strong wave action, a water-in-oil emulsion is created. Stable emulsions with up to 80% water can be encountered and are extremely viscous, presenting significant problems in a cleanup operation.

Figure 1 shows the viscosities of F80 fuel oil and water-in-oil emulsions at different temperatures, measured at a low shear rate. It should be noted, however, that the oil and water-in-oil emulsions are non-Newtonian fluids at low temperatures; subjecting them to a high shear rate will lower the viscosity and improve pumpability.

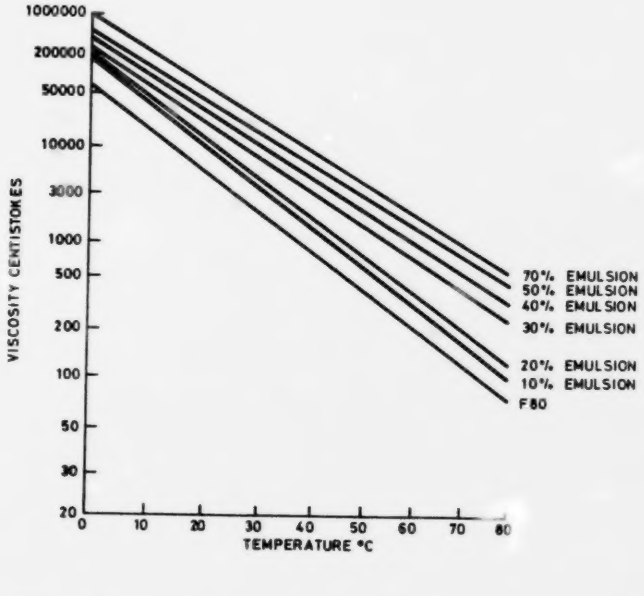

FIGURE 1 VISCOSITY OF F80 FUEL OIL AND F80 FUEL OIL EMULSIONS AT A SHEAR RATE OF 5 s$^{1}$

The pour point of F80 fuel oil is approximately -1°C. This is the temperature at which the oil does not flow, becoming a solid-like mass that floats on the water. Its rate of spreading is diminished and there is an increased tendency for a slick to break up. The table below summarizes the relevant physical properties of a typical F80 (3500 Redwood No. 1 seconds) fuel oil:

| | | | | |
|---|---|---|---|---|
| Specific Gravity at 15°C | - | 0.995 | | maximum |
| Flash Point | - | 66°C | | minimum |
| Pour Point | - | -1°C | | minimum |
| Viscosity at 82.2°C | - | 70 | cSt | maximum |
| 40°C | - | 800 | cSt | |
| 20°C | - | 5,000 | cSt | |
| 15°C | - | 9,000 | cSt | |
| 10°C | - | 17,000 | cSt | |
| 5°C | - | 33,000 | cSt | |
| 0°C | - | 70,000 | cSt | |

## ASSESSMENT OF RECOVERY PRINCIPLES

Many types of skimmers and pumps have been used to recover viscous oil and water-in-oil emulsions, with varying degrees of success. An assessment has been made of the different recovery principles involved; the factors which limit their performance when handling fuel oil at low temperatures have been identified. The recovery principles are classified into weir, belt, disc, vacuum and pump, as outlined in Figure 2.

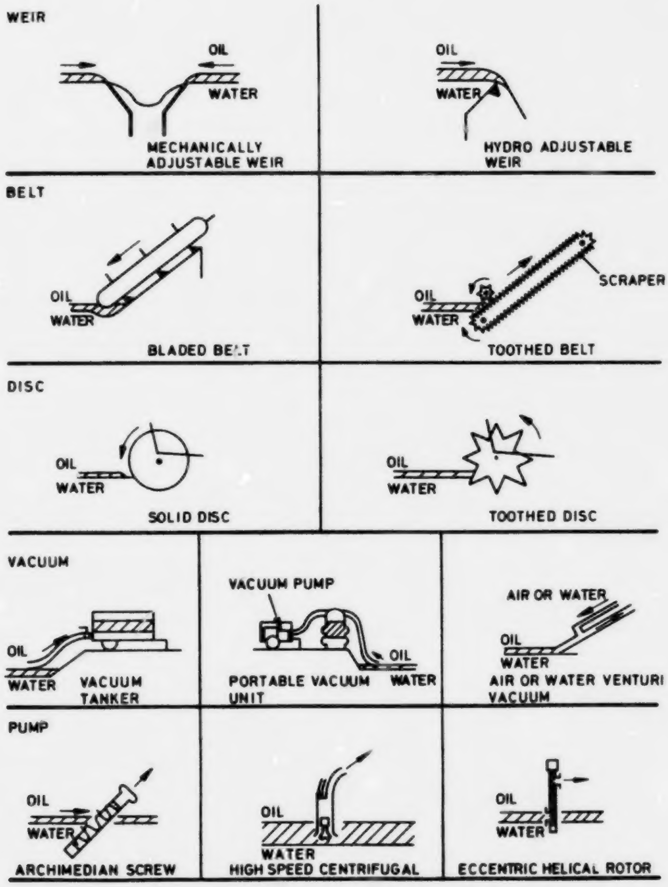
WEIR
OIL
WATER
MECHANICALLY ADJUSTABLE WEIR
OIL
WATER
HYDRO ADJUSTABLE WEIR
BELT
OIL
WATER
BLADED BELT
SCRAPER
OIL
WATER
TOOTHED BELT
DISC
OIL
WATER
SOLID DISC
OIL
WATER
TOOTHED DISC
VACUUM
OIL
WATER
VACUUM TANKER
VACUUM PUMP
OIL
WATER
PORTABLE VACUUM UNIT
AIR OR WATER
OIL
WATER
AIR OR WATER VENTURI VACUUM
PUMP
OIL
WATER
ARCHIMEDIAN SCREW
OIL
WATER
HIGH SPEED CENTRIFUGAL
OIL
WATER
ECCENTRIC HELICAL ROTOR

FIGURE 2 ASSESSED RECOVERY PRINCIPLES

The main limitation restricting recovery is the viscosity of the oil. The viscous oil does not readily flow towards the equipment or into the voids created by the skimming or pumping action. Also, the positioning of the inlet at the oil-water interface results in large volumes of water being recovered with the oil. A separator is therefore required to deal with the free water collected.

Skimmer and pump performances decrease when wave action and sea swell are encountered. The adverse effects are greatest on equipment which either requires fine adjustment of the inlet or is an integral part of the deployment vessel.

Recovery efficiency is also reduced when thin oil slicks are encountered. The performance of the equipment can be improved by using booms to concentrate the oil, increasing its thickness and thus improving the ratio of oil to water recovered. Many recovery devices are susceptible to debris which can restrict the flow of oil. Manual removal of the debris is considered preferable to debris screens which would only further impede the flow of oil. A study of the various factors which limit the performance of different recovery principles leads to the definition of the requirements which govern effective viscous oil recovery.

## REQUIREMENTS FOR EFFECTIVE VISCOUS OIL RECOVERY

An effective viscous oil recovery skimmer requires a mechanism which continuously draws in the oil to load the skimmer. This is necessary due to the high viscosity, low flow, and reduced spreading characteristics of the oil. The equipment should operate effectively when subjected to wave action and sea swell. Wave motion induces a lag on the recovery equipment motion with respect to the oil-water surface and results in localized oil displacement. This action tends to break up the continuous oil slick being recovered. The lag is much worse if the skimmer is fixed to the deploying vessel due to the latter's greater inertia. This can be alleviated to some extent by using a universal joint or flexible link between the equipment and the vessel.

A debris handling capability is necessary. The equipment should be designed to enable oil recovery to continue in the presence of hard debris which may become entrapped on the recovery mechanism. It is also necessary to include a means of transferring the recovered oil from sea level to a storage facility on board the deployment vessel. Installing a pump on the recovery equipment takes advantage of its pressure discharge capability. Free water recovered with the oil should be kept to a minimum, to eliminate the need for an onboard oil-water separation system. However, it is appreciated that small amounts of free water with the oil improve pumpability. The recovery equipment should be easy to deploy, operate, and recover, and be as simple and robust as possible to avoid extensive maintenance problems.

## VISCOUS OIL RECOVERY EQUIPMENT DEVELOPMENT

Equipment embodying the above requirements consists of vertical arrays of toothed discs and a discharge pump. When a pair of disc arrays is contra-rotated, oil is drawn in and a head of oil is generated to feed the pump which is positioned above the waterline. This arrangement minimizes free water recovery. Having the disc arrays extending into the water enables continuous oil recovery to take place when the equipment is subjected to wave motion.

### Equipment Design

The principle behind the equipment design is based on the adaptation of a toothed disc and toothed belt device invented by Mr. E.V. Byers, MC., BSc., Nottingham, England, as outlined in Figure 2. The device is comprised of a horizontal array of interleaving discs, with teeth projecting from an endless conveying belt. With the disc and belt inlet positioned at the oil-water interface and contra-rotated towards each other, viscous oil is drawn in and recovered. This arrangement is effective in drawing in the oil because the teeth pierce the oil and, by their motion, induce a tensile pull on the cohesive viscous oil mass.

However, the belt inlet throat required fine adjustment when subjected to sea swell; the configuration was therefore turned through 90° so that the axis of the inlet throat was vertical. In this vertical mode, the toothed assembly intersects the oil water interface and is less affected by wave motion.

To collect the recovered oil, interleaving disc arrays are attached to an oil collection tube. When the disc arrays are operated, oil is drawn in, caught between the discs, and pushed through an opening into the collection tube. A scraper arrangement prevents the collected oil from flowing out of the tube. Continuing to rotate the discs fills the tube with oil. The action of the rotating discs generates a pressure head within the collection tube which is sufficient to sustain a column of viscous oil.

The action of the discs in sustaining a column of oil is a valuable feature. A pump can then be attached to the collection tube above the waterline and the resulting pressure head used to feed the oil into the pump inlet. Positioning the pump above the waterline minimizes the amount of free water recovered.

A further advantage of the equipment is the fact that it need not necessarily be positioned accurately relative to the oil-water interface. Having the disc arrays extending above and below the oil layer enables continuous oil recovery to take place when the equipment is subjected to wave motion.

## Equipment Development

Several viscous oil recovery prototypes have been developed. Experience gained from these was used to develop the current versions. A suspended skimmer, outlined in Figure 3 and designed for mobility over an oil slick area, would be particularly useful in confined spaces (close to jetties, dock walls, etc.). A floating type, outlined in Figure 4 and designed to operate in a free floating mode, would be suitable for harbour, coastal and offshore situations because of its shallow draft and high stability.

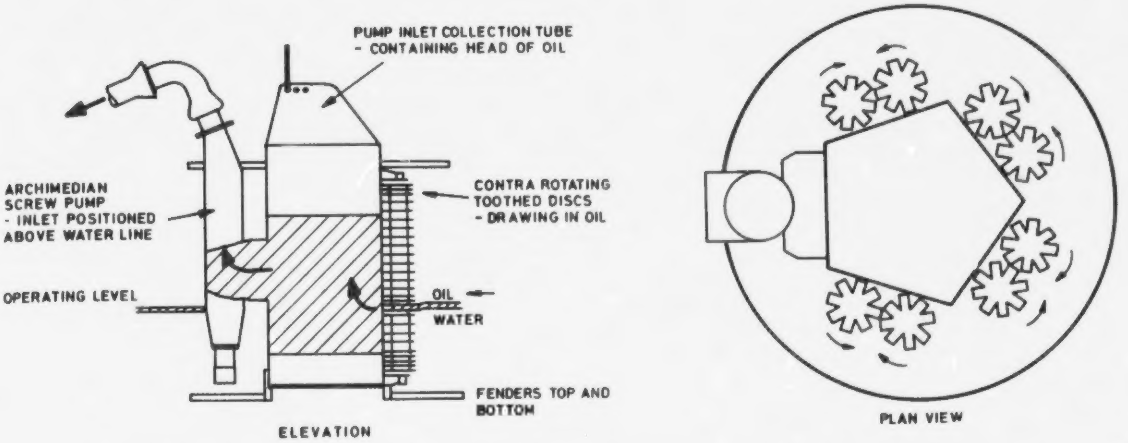
PUMP INLET COLLECTION TUBE
- CONTAINING HEAD OF OIL
ARCHIMEDIAN
SCREW PUMP
- INLET POSITIONED
ABOVE WATER LINE
CONTRA ROTATING
TOOTHED DISCS
- DRAWING IN OIL
OPERATING LEVEL
OIL
WATER
FENDERS TOP AND
BOTTOM
ELEVATION
PLAN VIEW

FIGURE 3 ROTATING TOOTHED DISC AND SCREW PUMP DEVICE - SUSPENDED TYPE

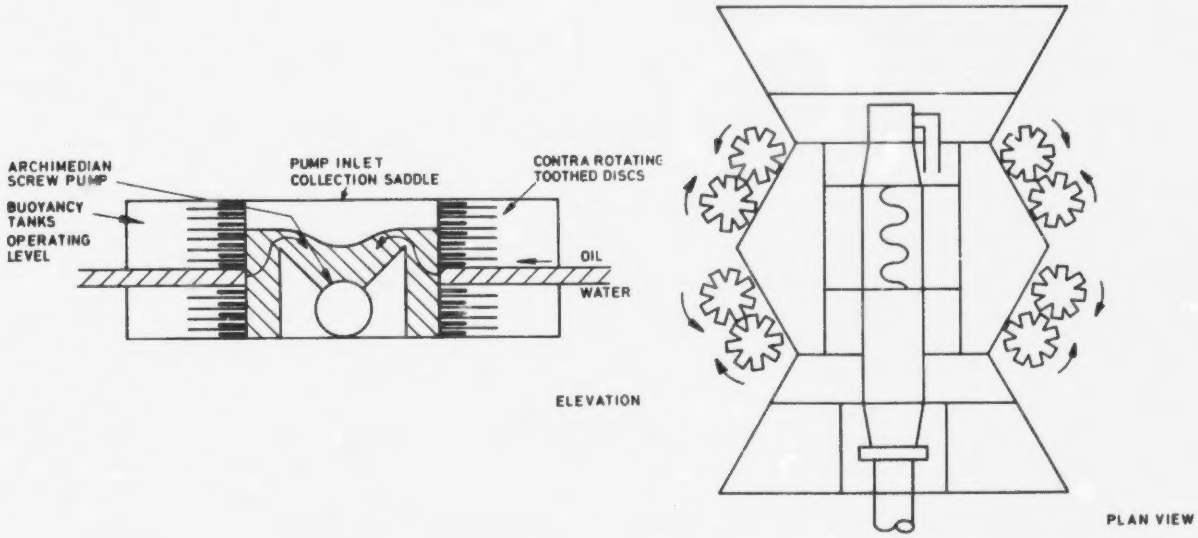
ARCHIMEDIAN
SCREW PUMP
BUOYANCY
TANKS
OPERATING
LEVEL
PUMP INLET
COLLECTION SADDLE
CONTRA ROTATING
TOOTHED DISCS
OIL
WATER
ELEVATION
PLAN VIEW

FIGURE 4 ROTATING TOOTHED DISC AND SCREW PUMP DEVICE - FLOATING TYPE

Each skimmer has four skimming modules, each consisting of two contra-rotating vertical shafts on which toothed discs are located at equal intervals to form disc arrays. The disc array on one shaft is off-set half an interval relative to that on the other shaft, giving an interleaving structure. The discs are made of a rigid plastic material able to withstand impact and distortion. Two meshing gears driven by a slow-speed hydraulic motor contra-rotate the disc arrays. The four skimming modules, each with its own hydraulic motor, are attached to pump inlet collection tubes (Figures 3 and 4).

The suspended skimmer has an Archimedean screw pump attached vertically to the pump inlet collection tube. The pump transfers the recovered oil to storage tanks on the deployment vessel or jetty. This type of pump was chosen because its features include a short pump intake with a large throat, the ability to handle soft debris, a positive discharge capability with pressures up to 7 bar, and proven ability to handle viscous oil and water-in-oil emulsions. The floating skimmer employs the same pump installed horizontally. Straddling the pump intake is a collection tube saddle to which the interleaving toothed disc arrays are attached. All skimmers are installed in a framework and supported by buoyancy tanks when deployed.

Each skimmer is powered hydraulically via umbilical hoses from remote diesel-driven powerpacks. There are two flow and pressure controlled hydraulic supplies and a common return from the powerpack to each skimmer. One of the supplies feeds the discharge pump hydraulic motor and the other feeds, through a rotary flow divider and relief valve block, each of the hydraulic motors driving the skimming modules. A rotary flow divider is incorporated to distribute the flow of hydraulic oil equally, to ensure that each disc array rotates at the same speed. A relief valve block is added to protect the flow divider should an overload situation occur. The speeds of the discs and discharge pump are controlled from the powerpack and can be varied to achieve the optimum oil recovery rate.

The recovery skimmers can handle soft debris such as seaweed, plastics, etc. If solid debris is encountered, it may be entrapped on the disc arrays of a skimming module, preventing rotation. Should this occur, the hydraulic system described above allows the remaining modules to continue operating at their set speed, recovering the viscous oil.

The capacity of the skimmers, especially when pumping viscous oil and water-in-oil emulsions, is related to the backslip through the discharge pump. The diameter and length of hose are important factors in minimizing back pressure and maximizing discharge capacity.

To select the optimum conditions in which the pump will discharge the recovered viscous oil, a simple guide to the relationship between the fluid conditions, pressure drop, and pipe diameter is given. This allows the flow rate to be estimated for a given pipe bore and viscosity of the oil. The correlation used is for laminar flow of viscous Newtonian oils and non-Newtonian oils at a particular shear rate. The correlation is given below in imperial and SI units.

$$Q = \frac{182{,}900 \times D^4 \times P}{S \times V \times L} \quad \text{gallons/hour} \tag{1}$$

where $Q$ = flow, in UK gallons per hour
$D$ = bore of pipe, in inches
$L$ = length of pipe, in feet
$P$ = pressure drop, in lbs/square inch
$S$ = specific gravity relative to water
$V$ = viscosity, in centistokes

$$Q = \frac{0.0883 \times D^4 \times P}{S \times V \times L} \quad \text{litres/hour} \tag{2}$$

where $Q$ = flow, in litres per hour
$D$ = bore of pipe, in millimetres
$L$ = length of pipe, in metres
$P$ = pressure drop, in kN/m$^2$
$S$ = specific gravity relative to water
$V$ = viscosity, in centistokes

### Equipment Deployment

Both types of viscous oil recovery skimmers are designed to be deployed, operated, and recovered from vessels, jetties and harbour walls equipped with cranes. To maximize the oil recovery rate, the skimmers should be used in conjunction with an oil containment boom where oil thickness can be increased. However, the skimmers can be used on thin oil slicks and patches.

The suspended skimmer has a built-in single lifting point; suspended from a crane, it can be manoeuvred over viscous oil floating in patches or contained within a boomed area. When the skimmer is used in conjunction with a containment boom, steel fenders are fitted to prevent the toothed discs from damaging the boom.

The floating skimmer is designed to be independent of the deployment vessel after launching and can be deployed either within a containment boom or in a sweeping boom configuration to recover drifting oil. To operate in the sweeping boom configuration, booms are attached to the appropriate buoyancy tanks to form a "V"-shaped arrangement; the oil is concentrated at the bottom of the "V" where the skimmer is placed. This configuration could operate as a single ship system and would be particularly useful in open sea situations to recover oil which has been formed into windrows.

## EQUIPMENT EVALUATION

Earlier prototypes of the suspended and floating viscous oil recovery skimmers, having only two skimming modules, were evaluated. Test tank and sea trials were undertaken to prove the operating principles and obtain performance data. Oil used in the trials was F80 (3500 Redwood No. 1 seconds) fuel oil which gradually emulsified, due to the continuous recovery and pumping action, to form a 50% water-in-oil emulsion. The apparent viscosity of the oil ranged from 14,000 centistokes for F80 at 13°C to 400,000 centistokes for 50% water-in-oil emulsion at 2°C. The viscosity was measured at a low shear rate of 5 reciprocal seconds.

When the tank trials took place, the skimmers were deployed with the discs intersecting layers of oil up to 75 mm thick. For water-in-oil emulsions having apparent viscosities of 70,000 cSt at 10°C and 400,000 cSt at 2°C, the recovery rates obtained were 6.5 $m^3/h$ and 2.0 $m^3/h$, respectively. In all cases, the oil recovered had a free water content of less than 2%.

The pumps discharged the oil through 125 mm diameter hose, 15 m in length, and was subjected to a maximum back pressure of 6.3 bar. The disc and discharge pump hydraulic motors were powered from 22 kW powerpacks and required 52 L/min of hydraulic oil at 100 bar.

When sea trials were undertaken, the skimmers were deployed within a boomed area in a harbour and the following observations were made:

(a) Low viscosity oil, 14,000 centistokes at 13°C, in a thin layer, 2 mm thick, was recovered at a rate of 1 $m^3/h$. By reducing the boomed area to increase the oil thickness, an improvement in the oil recovery rate was obtained.

(b) Viscous oil and water-in-oil emulsions were drawn into the skimmer by the action of the contra-rotating toothed discs from a distance of more than 6 m.

(c) With the skimmers deployed in a 7 mm layer of a 30% water-in-oil emulsion having an apparent viscosity of 125,000 centistokes at 5°C, recovery rates of 5 $m^3/h$ were achieved. The pumps on both skimmers discharged the oil through 125 mm diameter hose, a height of 2.5 m and a distance of 11 m when subjected to a back pressure of 4 bar. The recovered water-in-oil emulsion had a free water content of less than 2%.

(d) Oil continued to be recovered when the skimmer was subjected to a sea swell.

(e) Soft debris recovered with the oil was handled by the skimmer. When hard debris was entrapped on a skimming module, preventing rotation, the other module continued operating, recovering the viscous oil.

The evaluation trials successfully demonstrated the ability of the prototype suspended and floating skimmers to recover viscous oil and water-in-oil emulsions from the surface of the sea. Suspended and floating skimmers, with configurations as outlined in Figures 3 and 4 and having the ability to handle 20 $m^3/h$ of viscous oil, have now been developed incorporating the experiences gained from the trials.

## ACKNOWLEDGEMENTS

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# SESSION IV-C DISPERSANTS

## EFFECTIVENESS AND TOXICITY OF OIL DISPERSANTS

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### INTRODUCTION

A group at the Department of Microbiology and Plant Physiology (IMP) at the University of Bergen, Norway, has been working since 1976 with toxicity testing of oil dispersants on green algae (Heldal et al., 1977; Bratbak et al., 1982). A toxicity test was developed to be used by the State Pollution Control Authority (SFT) for approval of oil dispersants for use in Norwegian Waters (Anon., 1980). Two observations made from this relatively early work were that a mixture of oil and dispersants generally is more toxic than either of the two compounds alone, and that the toxicity is strongly dependent on the oil-to-dispersant ratio. Further work, including some effectiveness testing, indicated a significant correlation between toxicity and effectiveness, and raised two questions:

(a) Is dispersed oil the main toxic component in the toxicity test?

(b) Does the toxicity test to some extent measure a dispersant's effectiveness? And, if so, should the experiments be redesigned to separate toxicity from effectiveness?

It was evident that further knowledge on dispersants was needed to answer these questions.

Combating oil spills in general and use of dispersants specifically are of national interest in Norway. Norway is an oil-producing country with a significant drilling activity on the continental shelf. In the event of an accident, this activity may lead to severe oil spills. Also, the Norwegian coast faces the North Sea, which has a relatively high traffic density of ships. This activity also represents a source of oil spills, either from dumping or in the event of a ship disaster.

Oil dispersants are part of the means that Norwegian Authorities will consider when combating possible oil spills at sea. It is therefore of great interest to identify those products which will work most effectively under varying conditions. At the same time, the environmental impact of a dispersant operation should be minimized; knowledge of the toxic effects of dispersants is therefore also required. Effective dispersants are preferred because smaller amounts have to be applied. An effective dispersant may be more toxic than a low-effective one, but the reduced amount used could compensate for this, and the overall environmental effect need not necessarily be worsened. It is, therefore, important to look for procedures of approval that make a combined assessment of both effectiveness and toxicity.

### EXPERIMENTAL

#### Testing of Effectiveness

Ten commercial oil spill dispersants are tested for effectiveness using the method described by Mackay and Szeto (1980). Several laboratory studies have been undertaken to evaluate different methods for effectiveness testing of dispersants (Rewick et al., 1980; Byford and Green, 1982; Meeks, 1981); the Mackay test has been one of the most common accepted methods, the main reason why it was selected in this study. Many factors influence the effectiveness of dispersants (Mackay et al., 1977); the following variables were studied in this work: type of dispersant, type of oil, dispersant-to-oil ratio, and temperature. The stability of the dispersion was also investigated for some of the dispersants tested.

Table 1 lists the dispersant products tested in the experiments. Also included in the table are those products which were approved and those which were not approved for use in Norwegian waters by January, 1983. All the products are concentrates; they are not diluted before application. Table 2 gives the oils used in the experiments, including some physical properties. The temperatures used in the experiments were mainly 13°C and 6°C, the mean temperatures in the North Sea during summer- and wintertime, respectively.

The dispersant-to-oil ratios (D/O-ratios) used in most of the experiments were 0.1/10 (1/100), 0.2/10 (1/50) and 0.5/10 (1/20). Some of the dispersants were tested at several other D/O-ratios, to get a more complete curve for effectiveness against D/O-ratio.

All the experiments were performed at an energy-level corresponding to an oxygen transfer coefficient of 17 cm/h; the salinity was 33 °/oo. The numbers are mean values of two or three parallel experiments at each D/O-ratio. Two water samples were taken for each experiment. One was taken after 10 min of mixing (sample 1) and another was taken after 5 min of settling to measure dispersion stability (sample 2).

TABLE 1 LIST OF DISPERSANTS INCLUDED IN THE TESTING PROGRAM

| | |
|---|---|
| Amoco Wellaid 331 | Approved for use in Norwegian waters |
| BP 1100 WD | Approved |
| Corexit 9600 | Approved |
| Corexit 9527 | Not approved |
| Finasol OSR 5 | Not approved |
| Finasol OSR 7 | Approved |
| Gamlen OD 2000 | Approved |
| OSD 41 | Approved |
| Quell-Oil C1 | Approved |
| R-OD-1 | Approved |

TABLE 2 OILS USED IN THE EXPERIMENTS AND SOME PHYSICAL PROPERTIES

| | Ekofisk Crude Oil | IF[a]-30 | IF[a]-180 |
|---|---|---|---|
| Density, in g/cm$^3$ at 15°C | 0.809 | 0.922 | 0.986 |
| Dynamic viscosity, in mPas, 13°C[b] | 5.9 | 290 | 8 300 |
| Dynamic viscosity, in mPas, 6°C[b] | 7.3 | 700 | 28 000 |

[a] IF = intermediate fuel
[b] Measured at a shear rate of 113 s$^{-1}$

### Testing of Toxicity

The toxicity tests in this study were performed using three different algae: two saltwater algae (*Dunaliella bioculata* and *Chlamydomonas vectensis*), and one freshwater alga (*Chlamydomonas reinhardti*). The methods used are described in more detail in the literature (Nes and Norland, 1983).

The dispersants tested, BP 1100 WD, Corexit 9527, Finasol OSR 5 and R-OD-1, are all concentrates and were tested in a standard dilution of 10. One part of concentrate and 9 parts of growth medium were thoroughly mixed. One part of this blend and one part of the test oil were mixed thoroughly. From this mixture, portions were transferred to test cultures to make a predetermined concentration series.

**Experiments with *Chlamydomonas reinhardti* and with *Dunaliella bioculata*.** Four of the dispersants mentioned earlier, BP 1100 WD, Corexit 9527, Finasol OSR 5 and R-OD-1, were tested for toxicity in combinations with five different crude oils from the North Sea (Ekofisk, Beryl, Brent, Flotta and Statfjord crude oils).

**Experiments with *Chlamydomonas vectensis*.** The same dispersants as above were tested in combination with two of the oils, Ekofisk and Statfjord crude oils.

## RESULTS AND DISCUSSION

### Effectiveness

**Experiments with Different Oils.** Table 3 gives the effectiveness results obtained for the D/O-ratios 0.1/10, 0.2/10 and 0.5/10 at 13°C using Ekofisk crude oil as test oil. Corresponding results are given for IF-30 in Table 4. The results in Tables 3 and 4 show that there are great variations in dispersing ability among the different products tested. Closer inspection makes it clear that three of the products (BP 1100 WD, Corexit 9527 and Finasol OSR 5) are more effective than the others in dispersing the oil into the water column, as well as in keeping the oil droplets dispersed in the water. Experiments undertaken with the two different oil types give the same ranking of the dispersants tested.

However, the most viscous oil, IF-30, generally gives somewhat lower effectiveness values. The viscosity of IF-30 at 13°C is 290 mPas, well within the range where the dispersants work most effectively, according to Martinelli and Cormack (1979). The difference in effectiveness between the various dispersants decreases as the D/O-ratio increases, as can be seen from the D/O-ratio of 0.5/10. This tendency may indicate that, for some dispersants, a greater volume of dispersants may partially compensate for the lower effectiveness of these products compared with BP 1100 WD, Corexit 9527 and Finasol OSR 5. On the basis of the results from sample 2 in the different experiments, the difference between the various dispersants is even clearer. Both sample 1 and sample 2 give the same ranking of the different products in terms of their effectiveness in dispersing the oil.

TABLE 3 EFFECTIVENESS RESULTS (PERCENT OIL DISPERSED) WITH EKOFISK CRUDE OIL AS TEST OIL AT 13°C

| | D/O-Ratio | | |
|---|---|---|---|
| Dispersant | 0.1/10 | 0.2/10 | 0.5/10 |
| Amoco Wellaid 331 | 54 (2) | 64 (4) | 92 (25) |
| BP 1100 WD | 89 (26) | 88 (37) | 87 (37) |
| Corexit 9600 | 54 (6) | 63 (9) | 73 (15) |
| Corexit 9527 | 89 (23) | 92 (49) | 93 (63) |
| Finasol OSR 5 | 94 (25) | 87 (36) | 78 (36) |
| Finasol OSR 7 | 51 (2) | 68 (3) | 89 (13) |
| Gamlen OD 2000 | 68 (3) | 81 (7) | 82 (11) |
| OSD 41 | 20 (4) | 19 (4) | 25 (1) |
| Quell-Oil C1 | 16 (1) | 26 (2) | 36 (4) |
| R-OD-1 | 52 (4) | 82 (12) | 93 (24) |

The numbers in parentheses give the amount of oil still in dispersion after 5 minutes of settling (sample 2).

TABLE 4 EFFECTIVENESS RESULTS (PERCENT OIL DISPERSED) WITH IF-30 AS TEST OIL AT 13°C

| | D/O-Ratio | | |
|---|---|---|---|
| Dispersant | 0.1/10 | 0.2/10 | 0.5/10 |
| Amoco Wellaid 331 | 5 (1) | 13 (2) | 19 (4) |
| BP 1100 WD | 86 (8) | 96 (37) | 96 (59) |
| Corexit 9600 | 14 (1) | 40 (4) | 61 (12) |
| Corexit 9527 | 88 (31) | 85 (38) | 91 (55) |
| Finasol OSR 5 | 60 (15) | 95 (18) | 100 (48) |
| Finasol OSR 7 | - | 9 (<1) | 14 (1) |
| Gamlen OD 2000 | 38 (3) | 36 (4) | 45 (6) |
| OSD 41 | - | 3 (<1) | 5 (<1) |
| Quell-Oil C1 | 4 (<1) | 11 (2) | 18 (6) |
| R-OD-1 | 18 (4) | 28 (6) | 44 (12) |

One single D/O-ratio, 0.2/10, was tested with the more viscous oil, IF-180, at 13°C. The dispersant used in this test was Corexit 9527, one of the most effective dispersants when using Ekofisk crude oil and IF-30. Only 4% of the oil was dispersed into the water in this case. The viscosity of this oil, measured at 13°C at a shear rate of 113 $s^{-1}$, was 8,300 mPas, within the viscosity region where the dispersant effectiveness is rapidly falling to zero, according to Martinelli and Cormack (1979).

**Experiments Performed at Different Temperatures.** When performing experiments at 13°C and 6°C, the temperatures of air, water, oil and dispersant were also 13°C and 6°C, respectively. Table 5 gives the results for BP 1100 WD and Corexit 9527 tested on Ekofisk crude oil at 13°C and 6°C. The same results are shown graphically in Figures 1 and 2. The effectiveness of BP 1100 WD and Corexit 9527 decreased somewhat, but not dramatically, when the temperature was lowered from 13°C to 6°C. The greatest deviation between these two temperature series occurred at the D/O-ratio of 0.05/10.

**Amount of Oil Dispersed as Function of Several D/O-ratios for Some Selected Dispersants.** Four of the dispersants used were tested at several D/O-ratios at 13°C using Ekofisk crude oil as a test oil. The results are given in Table 6. Figures 3 and 4 show the amount of oil dispersed as a function of the D/O-ratio for R-OD-1 and Finasol OSR 5.

The results indicate that BP 1100 WD, Corexit 9527 and Finasol OSR 5 were highly effective at dispersing the oil even at very low D/O-ratios. At the lowest D/O-ratio tested, 0.01/10, Corexit 9527 still dispersed the oil very well. It was, however, evident by visual observation that the oil droplets formed were much larger at this D/O-ratio, and were not able to remain dispersed after the energy input was stopped. For R-OD-1 for sample 1, an optimum effectiveness was attained at about a D/O-ratio of 0.4/10. Above this ratio, the effectiveness again decreased somewhat. A similar effect was obtained with Finasol OSR 5. The reason for this behaviour was not clear.

TABLE 5 EFFECTIVENESS RESULTS FOR BP 1100 WD AND COREXIT 9527 WITH EKOFISK CRUDE OIL AS TEST OIL AT 13°C AND 6°C

| | BP 1100 WD | | Corexit 9527 | |
|---|---|---|---|---|
| D/O-Ratio | 13°C | 6°C | 13°C | 6°C |
| 0.05/10 | 74 (6) | 61 (2) | 87 (15) | 67 (8) |
| 0.2/10 | 88 (37) | 85 (30) | 92 (49) | 82 (18) |
| 0.5/10 | 87 (37) | 89 (36) | 93 (63) | 85 (30) |
| 1.0/10 | 92 (42) | 91 (38) | 85 (35) | 89 (39) |

Numbers in parentheses give the results for sample 2 in the different experiments.

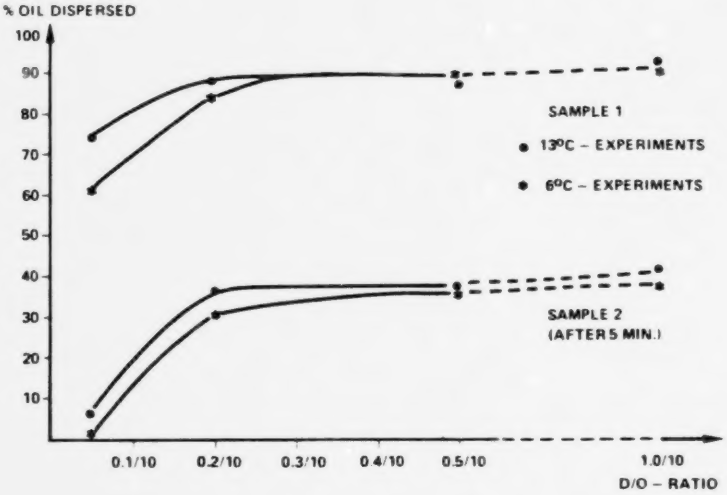

FIGURE 1 EFFECTIVENESS RESULTS WITH BP 1100 WD AND EKOFISK CRUDE OIL AT 13°C AND 6°C

## Toxicity Testing

**Experiments with *Chlamydomonas reinhardti.*** The results from the toxicity testing with *C. reinhardti* are summarized in Table 7.

**Experiments with *Dunaliella bioculata*.** The results from the toxicity testing with *D. bioculata* are summarized in Table 8. Again, the results were very similar for all combinations. However, some of the differences were statistically significant. Statfjord was apparently the most toxic oil, and Ekofisk and Brent less toxic. Finasol OSR 5 and Corexit 9527 were the dispersants with highest toxicity and BP 100 WD had the lowest toxicity.

**Experiments with *Chlamydomonas vectensis*.** The results from the toxicity testing with *C. vectensis* are summarized in Table 9. It can be seen that BP 1100 WD was much less toxic than any of the other dispersants tested, whereas the other dispersants were quite similar in toxic effect. For all dispersants used, Statfjord oil was slightly more toxic than Ekofisk; however, as some of the differences were quite small, the generality of this statement is uncertain.

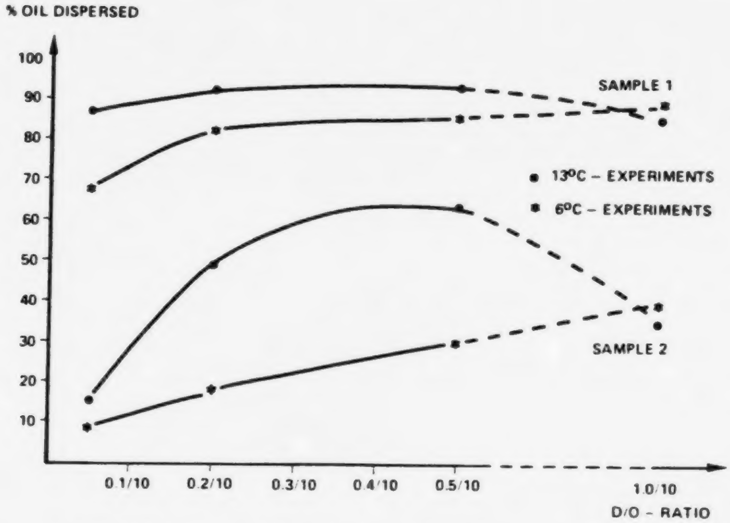

FIGURE 2 EFFECTIVENESS RESULTS WITH COREXIT 9527 AND EKOFISK CRUDE OIL AT 13°C AND 6°C

TABLE 6 AMOUNT OF OIL DISPERSED AS A FUNCTION OF SEVERAL D/O-RATIOS WITH EKOFISK CRUDE OIL AT 13°C

| D/O-Ratio | BP 1100 WD | Corexit 9527 | Finasol OSR 5 | R-OD-1 |
|---|---|---|---|---|
| | Dispersant | | | |
| 0.01/10 | 16 (4) | 72 (7) | - | - |
| 0.03/10 | 78 (2) | 79 (16) | 80 (7) | - |
| 0.05/10 | 74 (6) | 87 (15) | - | - |
| 0.08/10 | 86 (13) | - | 83 (35) | 44 (2) |
| 0.1/10 | 89 (26) | 89 (23) | 94 (25) | 52 (4) |
| 0.2/10 | 88 (37) | 92 (49) | 87 (36) | 82 (12) |
| 0.4/10 | - | - | 88 (39) | 94 (24) |
| 0.5/10 | 87 (37) | 93 (63) | 78 (36) | - |
| 0.8/10 | - | - | 74 (33) | 89 (32) |
| 1.0/10 | 92 (42) | 85 (35) | - | 78 (31) |

Numbers in parentheses give the results for sample 2 in the different experiments.

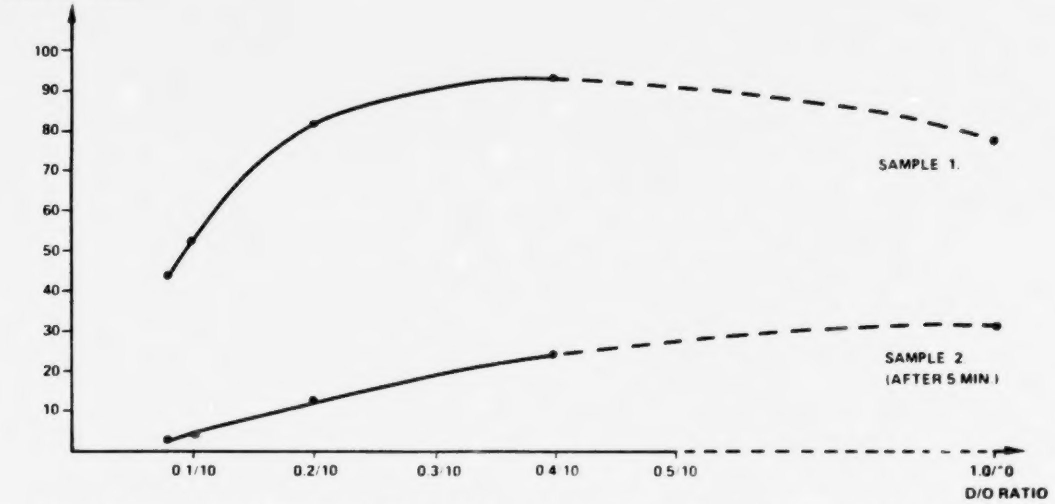

FIGURE 3 EFFECTIVENESS RESULTS WITH R-OD-1 AND EKOFISK CRUDE OIL AT 13°C

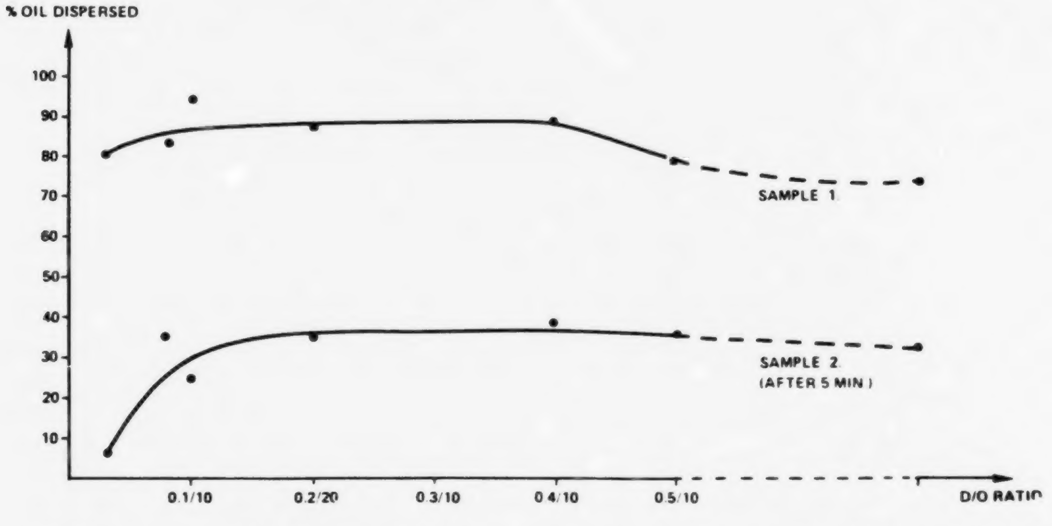

FIGURE 4 EFFECTIVENESS RESULTS WITH FINASOL OSR 5 AND EKOFISK CRUDE OIL AT 13°C

TABLE 7 RESULTS FROM TOXICITY TESTS WITH *CHLAMYDOMONAS REINHARDTI*, GIVING LC$_{50}$ VALUES IN PPM, REFERRING TO THE NOMINAL AMOUNT OF DISPERSANT IN THE TEST CULTURE. MEAN VALUES AND COEFFICIENTS OF VARIATION (CV) ARE INCLUDED

| | Dispersant | | | | | |
|---|---|---|---|---|---|---|
| Oil | Finasol OSR 5 | Corexit 9527 | BP 1100 WD | R-OD-1 | Mean | CV |
| Ekofisk | 36.1 | 35.5 | 12.7 | 14.4 | 24.7 | 0.53 |
| Beryl | 24.1 | 13.0 | 14.5 | 15.9 | 16.9 | 0.30 |
| Brent | 21.2 | 9.5 | 50.4 | 12.9 | 23.4 | 0.72 |
| Flotta | 12.0 | 50.0 | 9.7 | 30.0 | 25.5 | 0.73 |
| Statfjord | 27.1 | 71.2 | 19.3 | 18.6 | 34.0 | 0.74 |
| Mean | 24.1 | 32.3 | 21.2 | 18.4 | | |
| CV | 0.36 | 0.88 | 0.75 | 0.37 | | |

The differences between both rows and columns are small compared to the variation within groups. None of the differences are significant.

TABLE 8 RESULTS FROM TOXICITY TESTS WITH *DUNALIELLA BIOCULATA*

| | Dispersant | | | | | |
|---|---|---|---|---|---|---|
| Oil | Finasol OSR 5 | Corexit 9527 | BP 1100 WD | R-OD-1 | Mean | CV |
| Ekofisk | 6.0 | 4.7 | 18.5 | 5.2 | 8.6 | 0.77 |
| Beryl | 4.5 | 4.5 | 10.0 | 8.3 | 6.8 | 0.41 |
| Brent | 6.0 | 4.4 | 10.7 | 9.8 | 8.2 | 0.35 |
| Flotta | 4.6 | 5.5 | 9.6 | - | 5.6 | 0.27 |
| Statfjord | 3.8 | 2.6 | 4.1 | 5.0 | 3.5 | 0.28 |
| Mean | 4.7 | 4.4 | 11.2 | 7.6 | | |
| CV | 0.17 | 0.25 | 0.52 | 0.44 | | |

TABLE 9 RESULTS FROM TOXICITY TESTS WITH *CHLAMYDOMONAS VECTENSIS*

| | Dispersant | | | |
|---|---|---|---|---|
| Oil | Finasol OSR 5 | Corexit 9527 | BP 1100 WD | R-OD-1 |
| Ekofisk | 57 | 72 | 500 | 63 |
| Statfjord | 50 | 69 | 250 | 60 |

## CONCLUSIONS

### Effectiveness Testing

The results from the experiments performed with the Mackay test show great variability in dispersing ability among the different products tested. Experiments undertaken with the two different oils give the same ranking of the dispersants tested. The most viscous oil generally gives lower effectiveness values. Sample 2, taken after 5 minutes of settling, contributes valuable additional information on the stability of dispersions.

Experience from this work indicates the necessity of having a better cooling device for the airstream than the original one, when working at temperatures below about 10°C. The cooling device has been modified in this work, giving excellent temperature stability of the airstream when working at 6°C. Comparison of the laboratory test results with the limited amount of corresponding existing field experimental results is promising as far as the relative effectiveness of dispersants is concerned.

### Toxicity Testing

Of the three different algae used in the toxicity testing, it appears that the two saltwater algae, *Chlamydomonas vectensis* and *Dunaliella bioculata*, give a better discrimination between the dispersants tested. The freshwater alga, *Chlamydomonas reinhardti*, gives very similar toxicity results for most of the combinations of oils and dispersants tested.

The results from the tests for the two algae, *Dunaliella bioculata* and *Chlamydomonas vectensis*, agree on the following points:

- BP 1100 WD is less toxic than Corexit 9527 and Finasol OSR 5;
- Statfjord crude oil gives a more toxic mixture with dispersant and water than does Ekofisk crude oil;
- Of the five oils used as test oils, Ekofisk and Statfjord crude oils give a similar ranking of dispersant on the basis of toxicity.

A combined assessment of effectiveness and toxicity is desired, because these factors are found to be closely interconnected. At the moment, no method exists that takes care of this aspect, and effectiveness and toxicity are often evaluated separately. We feel that work has to be continued in this area to obtain an acceptable procedure for approval in which both the toxicity and the effectiveness of the dispersant are taken into account.

## ACKNOWLEDGEMENTS

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# FACTORS INFLUENCING THE PERFORMANCE AND SELECTION OF LOW-TEMPERATURE DISPERSANTS

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## INTRODUCTION

The risk of oil pollution in the Arctic arising from increased exploration has resulted in the use of chemical dispersants being considered as a possible countermeasure. The majority of currently marketed dispersants have been formulated to be effective in temperate climates when applied from ships. However, the size and isolation of Arctic areas will mean that the primary method of application will be from aircraft. Under these conditions, the only mixing energy available is from wind and wave action. Aerial application in cold climates will require higher standards of performance from dispersants for maximum effectiveness. The purpose of this study was to evaluate a selection of dispersants with respect to their physical properties and laboratory effectiveness at low temperature and in the presence of ice. These products were compared with an experimental formulation which was specifically developed for cold environments.

## SPECIAL FACTORS FOR ARCTIC DISPERSANTS

Use of dispersants in Arctic areas must take account of the low temperatures and presence of ice. These factors influence the properties required of a dispersant.

### Physical Properties

**Cloud and Pour Point.** The logistics of oil spill treatment may mean that stocks of dispersant will be kept in exposed locations for extended periods of time. They should therefore not separate, freeze, or gel at low temperatures. The lowest temperature experienced in storage conditions will determine the maximum cloud point desirable. Separation of even a small quantity of solid phase, i.e. at the cloud point, could cause problems in spraying operations by blocking nozzles. In this study, -30°C was chosen as the minimum temperature for storage during the period when aerial application is feasible.

**Viscosity.** The viscosity of the dispersant at a given temperature will determine its spraying behaviour (Lindblom and Cashion, 1983). The spraying equipment used will also affect the droplet size and swath width. The combination of dispersant viscosity, temperature, and spraying equipment should therefore be considered when evaluating dispersant use. If the viscosity of a dispersant is too low, it will produce very small droplets when sprayed, resulting in excessive wind-drift. Too high a viscosity may prevent the pumping equipment from delivering the required dose rate. The lower temperatures experienced in the Arctic will result in higher viscosities for existing dispersants, thereby making successful spray application more difficult with current equipment. In this study, the viscosities of the dispersants were determined at 0°C and -20°C to try to assess their suitability for aerial application at low temperatures.

### Effectiveness

**Low Temperature.** At low temperatures, the viscosity of any spilled oil is likely to be high. Even at low temperatures, crude oils will lose their light ends as they evaporate and become more viscous. While the limitations of dispersants in terms of the viscosity of oil to be treated are not well understood, it is widely accepted that very viscous oils are much less, if at all, amenable to treatment by dispersants.

**Salinity.** The salinity of seawater can be affected by the presence of ice. It has been stated that exclusion of salts by freezing can occur during periods of ice formation (Farmwald and Nelson, 1982). Melting ice can create a layer of lower-salinity water on top of the denser seawater. Wave action causes some mixing, but the salinity of the surface layer, where the dispersing action takes place, may be significantly lower. Consideration of bulk salinity may therefore be inappropriate, and the lower salinities at the surface should be considered.

**Low Energy.** The use of aerial application techniques will mean that the dispersant must be effective with only the mixing energy imparted by the action of the waves, in contrast to spraying operations from ships where additional agitation is supplied by the ship's movement or by towed breaker boards.

The presence of ice on the sea surface may damp the ripples or capillary waves which are thought to contribute the energy for dispersion (Mackay and Szeto, 1981), although the movement of ice pieces under the influence of the longer gravity waves may result in a "pumping" action on the water surface which will aid dispersion. The low energy performance of a dispersant is therefore of prime importance when selecting a product for use in the Arctic.

## DISPERSANT EVALUATION

In this investigation, a number of experiments were conducted to try and establish the following:

a) to identify and evaluate the most effective commercial dispersants for temperate conditions;

b) to determine the performance of the selected products in low salinity seawater and at low temperatures;

c) to compare the performances of the products in the presence of ice;

d) to determine the imporant physical properties of those dispersants and assess their significance for use in the Arctic.

An experimental formulation, which was specifically designed for use in cold environments, was also included in this study and compared with the selected commercial products.

### Test Methods

A large number of laboratory tests for assessing dispersant performance have been devised. While some correlation between tests can be obtained, it is generally difficult to make direct quantitative comparisons between methods (Rewick et al., 1981; Byford, 1982; Byford and Green, 1982). The only reliable justification for any laboratory test is that it can be correlated with performance at sea.

The Labofina rotating flask procedure is currently used by Warren Spring Laboratory (WSL) to assess the effectiveness of dispersants as part of the approval specification in the UK (Martinelli, 1982). Despite several criticisms of the method (Rewick et al., 1981; Byford and Green, 1982), the latest WSL version has shown some correlation with sea trials in ranking dispersant performance (Byford and Green, 1982; Martinelli, 1982). The method also has the advantages of speed and simplicity of operation, and consequently was used to evaluate a) and b) above.

For the evaluation of dispersants under temperate conditions, the Labofina tests using "Natura" synthetic seawater were conducted in a temperature-controlled room at 10°C. In each case, 0.1 mL dispersant/5 mL test oil was used. The low temperature and low salinity studies were carried out using the same volumes of dispersants and oil, with the whole operation being carried out at 0 to -1°C. The salinities used for each dispersant were 33 ppt (Natura synthetic seawater), 22 ppt, 11 ppt, 5.5 ppt and mains drinking water. The salinities between 33 ppt and freshwater were obtained by blending the synthetic seawater with mains drinking water.

Unfortunately, the Labofina test is not suitable for assessing dispersant performance in the presence of ice. An oscillating hoop test has been used to carry out some studies (Cox and Schultz, 1981), although repeatable results have not yet been obtained with this method. The BP wave tank test (Meeks, 1981) was found to be the most suitable for this study. In this procedure, 2 kg of freshwater ice were broken into irregularly shaped pieces, approximately 5 mm thick x 100 mm$^2$ area and added to the wave tank containing 25 litres of seawater at 0°C. This quantity of ice was sufficient to give 100 percent coverage of the water surface even during agitation. A 15 cm diameter plastic containment ring was placed on the ice/water surface followed by the addition of 10 mL of oil precooled to 0°C. The weight of oil used in each experiment was recorded. In these experiments with ice, it was found that the oil did not spread as on a clean water surface but ran into the crevices between the pieces of ice. Consequently, the surface area occupied by the oil was significantly less than the area of the containment ring.

This distribution of oil between the broken ice necessitated a different technique for applying the dispersant from that used in the Labofina test, i.e., dropwise from a syringe repette. An air-assisted spray applicator, previously used by Mackay (Mackay et al., 1980), was found to be suitable. Due to problems of overspray, it was found necessary to spray each dispersant through a 15 cm diameter by 36 cm long tube. Variation in dose rates, arising from different dispersant viscosities, was accounted for by calibrating the sprayer so that a known weight of dispersant could be applied evenly over the area inside the containment ring. Preliminary trials with the system showed that application of 0.5 g of dispersant to the containment area produced reasonable levels of dispersion. The dispersant was left for 1.5 minutes to diffuse into the oil, after which the ring was removed and the wave generator started. Wave amplitudes of about 40 mm were obtained. After 10 minutes of agitation, a 500 cm$^3$ sample of the dispersion was withdrawn and the oil concentration determined by extraction with chloroform and colorimetric comparison with standards at 580 nm. Considering the possible sources of variation in this procedure (for example, actual surface area of oil exposed to the spray), the results were fairly repeatable. While evaluation of dispersant performance in the presence of ice was the main reason for using the wave tank test, the dispersants were also assessed during the method at -1°C without ice being present. This also served to compare with the results from the Labofina test.

The physical properties of the dispersants which were determined included cloud point, pour point, and kinematic viscosity at 0°C and -20°C. Cloud and pour points below -30°C were not determined but recorded as <-30°C.

Three oils were used in the effectiveness tests. Selection of the most efficient dispersants for temperate conditions was made from the Labofina test performance against a medium fuel oil at 10°C. This is currently the method being considered by WSL for adoption in the UK. Additional data on the performance of these selected dispersants at 10°C was obtained using a 175°C residue of Lago Medio crude and a North Slope crude weathered by evaporation to a weight loss of about 11 percent. The Lago Medio 175°C residue and the 11 percent weathered North Slope residue were also used for the low salinity effectiveness tests and tank tests. Physical properties of the oils used are shown in Table 1.

TABLE 1 PHYSICAL PROPERTIES OF TEST OILS

| Property | Medium Fuel Oil | 175°C Topped Lago Medio Residue | 11% Weathered North Slope Residue |
|---|---|---|---|
| Dynamic Viscosity[a] (cP) at 10°C | 3 760 | 258 | 237 |
| Dynamic Viscosity[a] (cP) at 0°C | - | 3 180 | 1 660 |
| Density (g/cm$^3$) (cP) at 10°C | 0.9609 | 0.9080 | 0.9227 |
| Density (g/cm$^3$) (cP) at 0°C | - | 0.9102 | 0.9324 |
| Pour Point (°C) | 6 | -15 | 3 |

[a] Dynamic viscosities obtained at 10 $s^{-1}$ using a Haake Rotovisco RV2 viscometer.

## RESULTS AND DISCUSSION

### Dispersant Effectiveness Under Temperate Conditions

From the Labofina tests carried out on several concentrate dispersants at 10°C with medium fuel oil, six products were found to be significantly superior in terms of efficiency. In alphabetical order, these products were: Arcochem D609, BP 1100 WD, Corexit 9527, Corexit 9550, Dispolene 34S, and Finasol OSR5. For proprietary reasons, the dispersants were randomly coded A to F. The experimental formulation G, which was developed for use in cold environments, was also included in the study.

Table 2 shows the efficiency ratings of dispersants A to G in the Labofina test at 10°C against the medium fuel oil, together with results using the Lago Medio and North Slope residues. With the medium fuel oil, the commercial dispersants can be ranked B>D,E>F,C>A in efficiency. However, as the rest of the table shows, this ranking order can change dramatically if other oils are used. For the Lago Medio residue, the order is C,E>A,D>B,F, while for the North Slope residue it changes to C,A>D,E>F>B. This immediately highlights one of the problems of choosing a dispersant even on the sole basis of performance under temperate conditions. Although dispersant B is very effective against the viscous medium fuel oil, its performance is dramatically reduced when the lower-viscosity Lago Medio and North Slope residues are used. Conversely, while dispersant A is not very effective against medium fuel oil and Lago Medio residue, it is much more effective against the thinner North Slope residue.

TABLE 2 EFFICIENCIES OF SELECTED DISPERSANTS IN THE LABOFINA TEST AT 10°C AGAINST MEDIUM FUEL OIL, LAGO MEDIO AND NORTH SLOPE RESIDUES IN "NATURA" SYNTHETIC SEAWATER

| Dispersant | Medium Fuel Oil | 175°C Topped Lago Medio Residue | 11% Weathered North Slope Residue |
|---|---|---|---|
| A | 42,47 | 32,37 | 57,63 |
| B | 70,74 | 19,22 | 18,19 |
| C | 52,55 | 43,49 | 61,67 |
| D | 67,68 | 35,36 | 41,50 |
| E | 61,66 | 42,50 | 46,57 |
| F | 54,57 | 23,24 | 34,35 |
| G | 85,86 | 74,75 | 81,83 |

It has been shown that, using the Labofina test to evaluate dispersing efficiency as a function of oil viscosity, a pronounced maximum in performance occurs (Martinelli and Lynch, 1980). The initial increase in performance as viscosity increases is thought to be due to both the effects of increasing density and also increasing resistance to droplet coalescence. At higher viscosities, the resistance of the oil to deformation and droplet formation becomes the predominant factor and consequently performance is reduced. It has also been observed that, while different dispersants show similar efficiency/oil viscosity relationships, peak efficiencies vary, as does the viscosity at which the maximum occurs. Since different formulations do not exhibit a peak in performance at the same oil viscosity, differences in droplet coalescence rates, as well as degree of initial dispersion due to chemical effects, may well be important. It should not be surprising, therefore, that the dispersants tested are ranked in totally different orders if different oils are used. This illustrates that consideration must be given to the type of oil likely to be spilled in a particular area before selecting a suitable dispersant. The results of the tests on experimental formulation G, however, suggest that oil specificity can be reduced and may not be an insurmountable problem with dispersants.

### Performance Variation with Salinity at Low Temperature

The effect of water salinity on performance for dispersants A to G is summarized in Figures 1 to 6. Dispersants showing similar variations with salinity are included on the same graph. With the 175°C Lago Medio residue, the performance of dispersants A and C (Figure 1) was found to be proportional to salinity over the range studied. This was also generally true with the North Slope residue (Figure 2), although the dependence on salinity appeared to be much greater below 5.5 ppt.

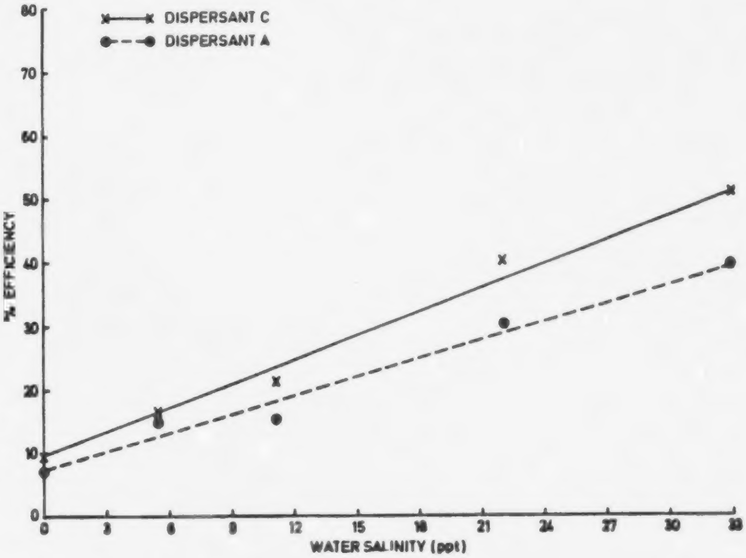

FIGURE 1 EFFECT OF WATER SALINITY ON DISPERSANT PERFORMANCE IN THE LABOFINA TEST AT 0°C AGAINST LAGO MEDIO RESIDUE

With both test oils, dispersants D and E showed a slight increase in performance with decreasing salinity down to 5.5 ppt (Figures 3 and 4). These increases may have been sustained below this level but dramatic reductions in performance were observed with freshwater. Dispersant F was generally less sensitive to changes in salinity, little change in performance being observed at salt concentrations greater than about 11 ppt. However, the overall performance of the product was significantly lower than that of dispersants D and E.

Dispersants B and G were found to be similar in their responses to changes in salinity, in that both appeared to be almost as effective in freshwater as at 33 ppt (Figures 5 and 6). Experimental formulation G showed some reduction in performance between these two extremes with the North Slope oil but its superior performance overall suggests that changes in salinity may not have a significantly adverse effect.

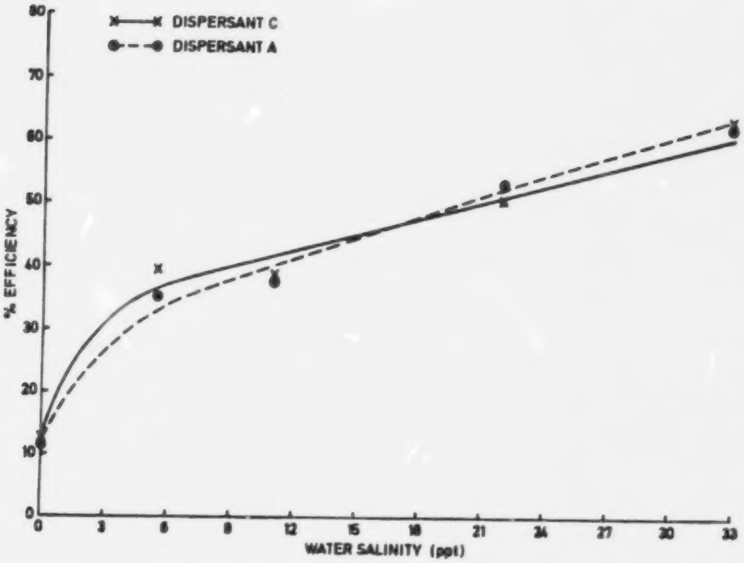

FIGURE 2 EFFECT OF WATER SALINITY ON DISPERSANT PERFORMANCE IN THE LABOFINA TEST AT 0°C AGAINST NORTH SLOPE CRUDE

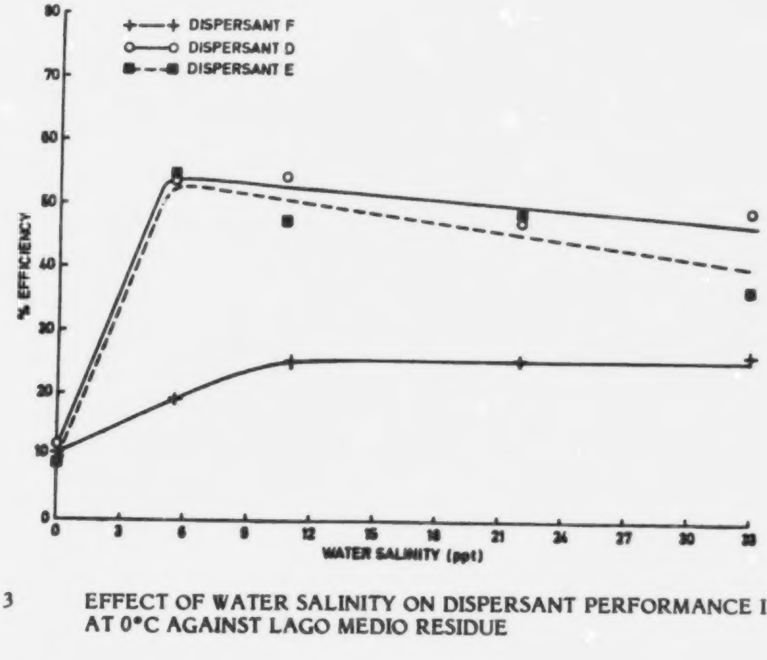

FIGURE 3 EFFECT OF WATER SALINITY ON DISPERSANT PERFORMANCE IN THE LABOFINA TEST AT 0°C AGAINST LAGO MEDIO RESIDUE

It is thought that the dispersion mechanism commences with an accumulation of surface active agents at the oil/water interface, resulting in a reduction in interfacial tension which promotes droplet formation. The oil droplets are then stabilized by the surface active agents via both the lower interfacial tension and the formation of solvate shells which inhibit droplet coalescence. While attempts have been made to explain the mechanism of the dispersion process by measuring fundamental parameters, such as interfacial tension and critical micelle concentrations at the oil/water interface (Rewick et al., 1980), to date there appears to be no single or combination of fundamental parameters which can

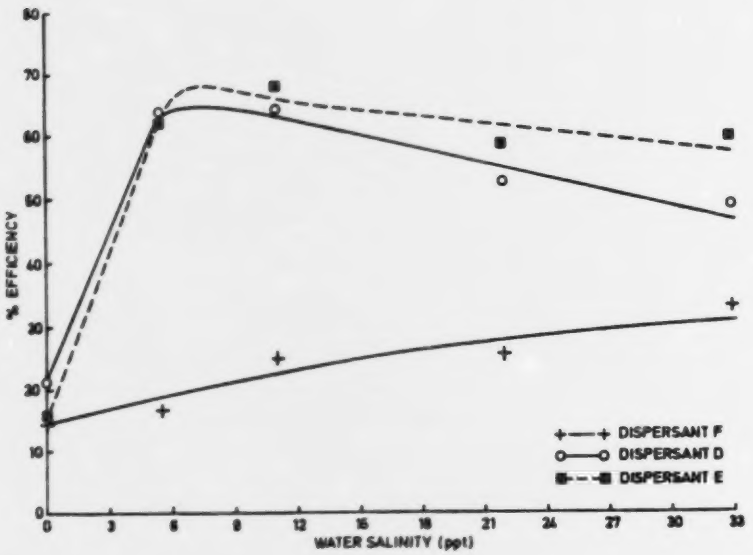

FIGURE 4 EFFECT OF WATER SALINITY ON DISPERSANT PERFORMANCE IN THE LABOFINA TEST AT 0°C AGAINST NORTH SLOPE RESIDUE

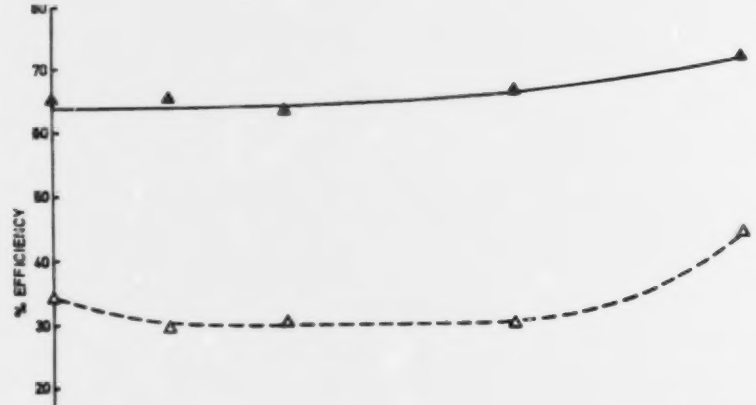

FIGURE 5 EFFECT OF WATER SALINITY ON DISPERSANT PERFORMANCE IN THE LABOFINA TEST AT 0°C AGAINST LAGO MEDIO RESIDUE

be used to accurately predict dispersant performance in a laboratory test. Despite this lack of understanding of the physico-chemical processes leading to the dispersion of oils, it seems intuitively reasonable to believe that salinity will affect the accumulation of both ionic and non-ionic surfactants at the oil/water interface and thereby influence both the extent of initial dispersion and the rate of coalescence. The results clearly show that these effects vary in magnitude with different dispersants.

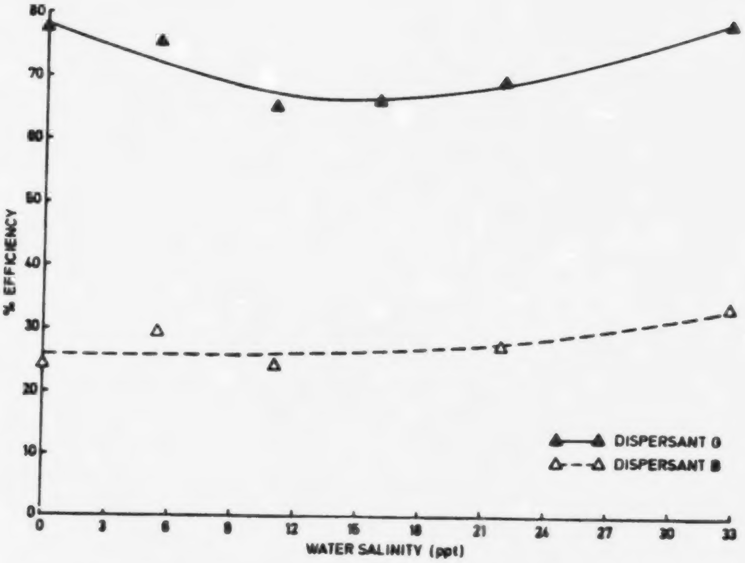

FIGURE 6 EFFECT OF WATER SALINITY ON DISPERSANT PERFORMANCE IN THE LABOFINA TEST AT 0°C AGAINST NORTH SLOPE RESIDUE

In addition to the physico-chemical processes of dispersion, changes in salinity will also affect the buoyancy of the oil droplets. Although the density of the seawater will not change very much between 0 and 33 ppt, the change in density difference between the seawater and oil will be much greater. Since droplet rise velocities are directly proportional to this difference in density, lower efficiency ratings could be obtained at higher salinities due to greater buoyancy. The steady decrease in efficiency from 5.5 ppt to 33 ppt observed with dispersants D and E (Figures 3 and 4) may be due to the effect of density difference overriding relatively insignificant chemical effects in this salinity range.

### Performance Variation with Temperature

Table 3 summarizes the Labofina test effectiveness ratings for dispersants A to G with the Lago Medio and North Slope residues at 10°C and 0°C using standard "Natura" seawater (33 ppt). It can be seen that, in nearly all cases, dispersant performance in this test is not impaired by the reduction in temperature. While the conclusion could be drawn that these dispersants are not sensitive to increasing oil viscosity over this range, it may also be due to the effect of increasing oil density or decreasing coalescence rates, resulting from increased viscosity, offsetting any reduction in the degree of initial dispersion. Obviously, dispersant performance would be dramatically reduced at much higher viscosities. It is also worth noting that the performance of dispersant B, which was very low with both oils at 10°C, is markedly improved by the reduction in temperature. The improved performance with the oils at 0°C and also with the medium fuel oil at 10°C seen earlier, suggests that this product might only be effective with viscous oils. It may be the case that, although it disperses thin and thick oils equally well, it is not effective at stabilizing the oil droplets once they have been formed; only when viscous oils are used, which have an inherent ability to resist droplet coalescence, does the overall performance improve.

### Dispersant Performance in the BP Wave Tank Test

**Without Ice.** The spraying system described previously was also used for experiments in the tank test at 0°C without ice present. The results are summarized in Table 4, which also includes the Labofina test results obtained at 0°C using "Natura" seawater. Comparison of the Labofina and tank test results shows a general lack of correlation between the dispersant ranking orders obtained from the two methods. It is felt that the generally poor correlation between the two methods is likely to be due to the different levels of agitation used in each method, which will affect the performance of dispersants to varying extents.

TABLE 3 EFFECT OF TEMPERATURE ON DISPERSANT PERFORMANCE IN THE LABOFINA TEST AGAINST LAGO MEDIO AND NORTH SLOPE RESIDUES IN "NATURA" SYNTHETIC SEAWATER

| | 175°C Topped Lago Medio Residue | | 11% Weathered North Slope Residue | |
|---|---|---|---|---|
| Dispersant | 10°C | 0°C | 10°C | 0°C |
| A | 32,37 | 39,40 | 57,63 | 57,67 |
| B | 19,22 | 41,45 | 18,19 | 33,34 |
| C | 43,49 | 47,55 | 61,67 | 62,63 |
| D | 35,36 | 46,52 | 41,50 | 47,51 |
| E | 42,50 | 35,39 | 46,57 | 58,62 |
| F | 23,24 | 24,28 | 34,35 | 29,37 |
| G | 74,75 | 69,73 | 81,83 | 77,79 |

TABLE 4 COMPARISON OF RESULTS ON SELECTED DISPERSANTS IN THE LABOFINA AND BP WAVE TANK TESTS AT 0°C USING LAGO MEDIO AND NORTH SLOPE RESIDUES

| | 175°C Topped Lago Medio Residue | | 11% Weathered North Slope Residue | | Total |
|---|---|---|---|---|---|
| Dispersant | Labofina Test | BP Wave Tank Test | Labofina Test | BP Wave Tank Test | Efficiency Rating |
| A | 39,40 | 28,32 | 57,67 | 35,39 | 337 |
| B | 41,45 | 44,50 | 33,34 | 61,71 | 379 |
| C | 47,55 | 39,46 | 62,63 | 40,48 | 400 |
| D | 46,52 | 56,60 | 47,51 | 33,38 | 383 |
| E | 35,39 | 39,44 | 58,62 | 29,37 | 343 |
| F | 24,28 | 26,34 | 29,37 | 8,9 | 195 |
| G | 69,73 | 51,59 | 77,79 | 60,70 | 538 |

The poor correlation between the methods highlights one of the problems of evaluating dispersant performance in the laboratory. The development of a meaningful laboratory method for testing the efficiencies of dispersants presents some difficult problems as the number and variety of tests available indicate. The main reason for this is the lack of detailed knowledge of the processes involved in the dispersal of oil. If it were known exactly how various properties of the dispersant affected its performance at sea, these might be measured accurately by existing physico-chemical techniques. At present, however, much effort is placed on the difficult task of simulating sea conditions in the laboratory.

The most important requirement of a laboratory test is that it should reflect performance at sea. Unfortunately, sea trial performance data are lacking; this is indicative of the problems in carrying them out. The poor correlation between different laboratory tests does not necessarily mean that the results from a particular test do not reflect performance at sea but may only apply to particular sea conditions. As a result of the limited amount of information available on dispersant performance at sea, dispersant selection based on the results of a particular laboratory test may not be indicative of sea performance over a wide range of conditions and should be regarded with caution. However, despite the lack of correlation between methods, if a dispersant consistently performs well in a range of laboratory tests, it would seem reasonable to assume that it would perform better at sea than dispersants which do not perform well in any laboratory test or those whose performance is good in selected tests only.

On this basis, the total efficiency rankings for each dispersant in the two tests with both oils were used to assess and compare the overall performances (Table 4). Using this approach, the results suggest that dispersant F would be much less effective than dispersants A to E, while experimental formulation G would provide the best chance for successfully treating oil at sea.

**With Ice.** Results of the dispersant tests using freshwater ice are summarized in Table 5. Comparison of the results with those obtained without ice (Table 4) shows that, in nearly all cases, dispersant performance is at least as good and often considerably better when ice is present. This is in contrast to the findings of Mackay et al. (1980), although Cox and Schultz (1981) found no reduction in dispersant performance in oscillating hoop tests with up to 50 percent ice cover. The apparently conflicting evidence regarding the relative performance of dispersants in the absence and presence of broken ice may be due to the ice having a dual effect on the energy of the system. One effect will be to damp the wave motion while an additional effect may be a pumping action imparted to the oil between the ice pieces. The damping effect may be more important at low energy levels, resulting in decreased dispersant performance in the presence of ice; under higher energy conditions, however, the pumping action which promotes dispersion may override the damping effect, leading to enhanced performance. Further work is necessary to establish the validity of this explanation and its relevance to dispersing oil under various conditions in ice-infested seas. The efficiency rates in Table 5 once again show that dispersant F is the least effective of those tested, while experimental formulation G exhibits a consistently high performance with both oils.

TABLE 5 EFFICIENCIES OF SELECTED DISPERSANTS IN THE BP WAVE TANK TEST AT 0°C IN THE PRESENCE OF ICE

| Dispersant | 175°C Topped Lago Medio Residue | 11% Weathered North Slope Residue |
|---|---|---|
| A | 21,30 | 39,44 |
| B | 62,67 | 71,75 |
| C | 60,69 | 48,50 |
| D | 58,66 | 73,78 |
| E | 40,50 | 57,61 |
| F | 19,22 | 30,32 |
| G | 90,95,98 | 96,99 |

## DISPERSANT PHYSICAL PROPERTIES

The physical properties of the dispersants evaluated are summarized in Table 6. The results of cloud point determinations show that dispersants D and F did not meet our chosen maximum of -30°C. In addition, dispersant D had a freezing point of -20°C and would therefore be considered by us to be unsuitable for Arctic use. The other commercially available products and the experimental formulation have, in our view, suitable cloud and pour points for storage at low temperature.

The viscosity data contained in Table 6 reveal that these dispersants can be considered as three distinct groups. Dispersant F is a low viscosity material, whilst A, C and G possess similar viscosities of $\backsim$800 cSt at -20°C and 160-170 cSt at 0°C. Dispersants B and E both have much higher viscosities at -20°C.

The effect of dispersant viscosity in aerial application has been considered by Lindblom and Cashion (1983). Dispersants having a low viscosity at the spraying temperature will produce very fine droplets when sprayed from aircraft, as was observed at the Suffield trials (Gill, 1981), and this will result in excessive wind drift. Dispersant F could exhibit similar behaviour if sprayed at temperatures above 0°C, although this effect would decrease as the viscosity increased at sub-zero temperatures. With aerial application at Arctic temperatures, however, a problem may be encountered as a result of the increased dispersant viscosity. This is not due to an increase in the size of the droplets produced, which would result in lower effectiveness, since aerodynamic shear forces reduce all but the more viscous fluids to less than 500 $\mu$ volume mean diameter under normal operating conditions. The practical maximum viscosity limit is likely to be set by the ability of the pumping system to deliver the correct dosage rate. The viscosities of dispersants B and E are higher than those of A, C and G and this may be a disadvantage if the pumping equipment available is the limiting factor. It is imperative, therefore, that the maximum viscosity of dispersants that can be pumped at the correct dose rate is determined for the particular application systems available.

TABLE 6 PHYSICAL PROPERTIES OF SELECTED DISPERSANTS

| Dispersant | Cloud Point (°C) | Pour Point (°C) | Kinematic Viscosity (cSt) | |
|---|---|---|---|---|
| | | | 0°C | -20°C |
| A | <-30 | <-30 | 170 | 850 |
| B | <-30 | <-30 | 286 | 1,830 |
| C | <-30 | <-30 | 158 | 778 |
| D | -20[a] | -20[a] | 220 | - |
| E | -30 | <-30 | 316 | 1,952 |
| F | -15 | <-30 | 40 | 95 |
| G | <-30 | <-30 | 170 | 850 |

[a] Freezes at this temperature

## SUMMARY AND CONCLUSIONS

The selection of optimal dispersants for aerial application in the Arctic necessitates careful consideration of their physical properties and effectiveness. Important physical properties include low cloud and pour points; these are essential for Arctic use under certain conditions and should be below commonly encountered storage and application temperatures. Equally important is the dispersant viscosity at low temperatures, since the spraying equipment may not be able to deliver the correct dosages of higher viscosity products.

Of the commercial products evaluated, two were found to have insufficiently low pour and cloud points for us to consider them generally suitable for use in the Arctic. The viscosity data are more difficult to use to select dispersants since the maximum viscosity limits for various application systems have not been considered. However, in our study, two dispersants were found to have much higher viscosities at sub-zero temperatures than the others; this could preclude their use with currently available equipment. From our considerations of all the physical properties likely to be required, only two commercial dispersants, together with an experimental formulation, appeared to be likely contenders.

Effectiveness testing using the Labofina method at 10°C showed that even the best commercially available products vary in performance with different oils, although the experimental formulation was relatively unaffected. The overall effectiveness against several oils, rather than performance on one oil, should therefore be used when assessing dispersants for general use.

Comparison of Labofina test results obtained at 10°C and 0°C with two oils showed that, in nearly all cases, dispersant performance was not impaired at the lower temperature, and even improved with some dispersants.

The performance of most dispersants was affected by the salinity of the seawater. This occurred to varying degrees, depending on the dispersant and oil used. One commercial product and the experimental formulation were virtually insensitive to salinity changes over the range studied, although the commercial product had a lower performance overall. In view of the dependence of dispersant performance on salinity, this aspect should be considered in the selection of products.

Results from tests in the presence of ice suggest that chemical dispersion may be enhanced by a pumping action between the broken ice pieces. Further work is needed to establish the effect of mixing energy on dispersion levels with ice present since effectiveness may be reduced at lower energies. Dispersant performance at different levels of ice coverage should also be studied.

In conclusion, the results of our study suggest that the best commercially available dispersants for use in temperate conditions may not be ideally suited for the more demanding conditions which prevail at lower temperatures. Inadequate physical properties at low temperatures in terms of viscosity, cloud and pour points, varying levels of performance with different oils, or reduced effectiveness in low salinity seawater appear to be the major factors for concern. Tests conducted with an experimental formulation specifically designed for use in cold environments show that products can be developed which are significantly better than those presently available.

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# EFFECTIVENESS OF CHEMICAL DISPERSANTS: A DISCUSSION OF RECENT PROGRESS

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## INTRODUCTION

A number of studies have been conducted at the University of Toronto in the last few years on aspects of the chemical dispersion of oil spills. This review lists these studies and highlights some of the conclusions and opinions which have been reached.

## LABORATORY EFFECTIVENESS TESTS

In an Exxon-supported project, we standardized the experimental conditions of the Mackay Nadeau Steelman (MNS) effectiveness test and demonstrated that available dispersants differed greatly in effectiveness (Mackay and Szeto, 1981). In more recent studies, also supported by Exxon, we have explored the effects of oil weathering, temperature, salinity, turbulence and the mechanism of contacting the oil with dispersant. An attempt has been made to develop correlating equations for effectiveness which are potentially applicable to other tests and to oceanic application conditions. This report, which will be available in mid-1983, quantifies these effects for several oils and dispersants.

It is clear that chemical dispersion is a very complex phenomenon influenced profoundly by the detailed transient physical and chemical processes which occur when dispersant drops mix with oil and migrate to the water. A study for BP on the effect of dispersant droplet size showed that small drops are considerably more effective than are large ones, probably because of the more effective mixing with the oil. Effectiveness is also oil and dispersant specific.

In a project for Aramco, we explored the effect of oil weathering (and, to a limited extent, emulsion formation) on effectiveness. It appears that weathering can influence effectiveness in either direction in a rather erratic manner until viscosity reaches the 2,000 to 8,000 cP range, when a strong viscosity effect depresses effectiveness. It seems likely that, in addition to viscosity, the oil composition plays an important role.

We also participated in a round robin in which the MNS test was evaluated in various laboratories in Canada, the U.S. and the U.K. The results of this program should be available shortly.

## TEST COMPARISONS

A considerable amount of work has been done comparing effectiveness tests, notably the MNS and the Labofina (or Warren Springs) rotating flask tests. It appears that these two tests may emerge as the accepted "standard" tests, and are complementary to each other. The MNS test is more expensive and more difficult to operate, but does yield more information; it has the inherent advantage that it simulates, at least to some extent, mixing conditions between air, water, oil and dispersant on a water surface. Correspondence between the two tests is fairly good. This issue has been addressed in a series of reports by BP (Byford, Green, Lewis and Meeks) and by the Warren Springs group (Morris, Crowley, Martinelli and Lee) published in the Oil Spill Conferences, the AMOP proceedings, the 1982 ASTM Conference at West Palm Beach, and as WSL project reports. At this stage, it may not be wise to devote much more effort to comparing these two tests until the extent to which either reproduces oceanic conditions is better elucidated.

### The Cascade Test

Having been impressed with the Warren Springs sea towing test, we have attempted to devise a similar laboratory test in which oil and dispersant are cascaded down an inclined slope over weirs. We are developing this test with BP support. In a short, exploratory study, we examined the effectiveness of three dispersants on Statfjord oil using the MNS system and the cascade system; we were able to compare the results with oceanic tests using the same oil and dispersants at similar temperatures. The oceanic tests were reported by Lichtenthaler and Daling (1983). Good agreement was obtained, thus suggesting that the MNS, cascade and oceanic tests are measuring the same basic phenomena. Clearly, further work of this type is very desirable, especially in cold Canadian waters.

### On-Scene Effectiveness Test

A recent project has been the development of a simple, on-scene dispersant effectiveness test with AMOP support. The only available test of this type is one marketed by Fina as part of their oil spill test kit.

The test procedure consists of taking an oil sample from the water and adding 10 mL to a volumetric flask (or a similar bottle) containing 1 L of seawater, such that the oil layer lies entirely in the neck of the bottle. A volume (usually 1 mL) of dispersant is then added and the flask rotated 30 times using a specified procedure as shown in Figure 1. The resurfacing of the oil is then observed and plotted; the amount which has resurfaced after 3 minutes is calculated and used as an indication of effectiveness. A connection for the water content of the oil may be necessary. No analytical instruments are needed. It is hoped that the procedure will be improved and tested further.

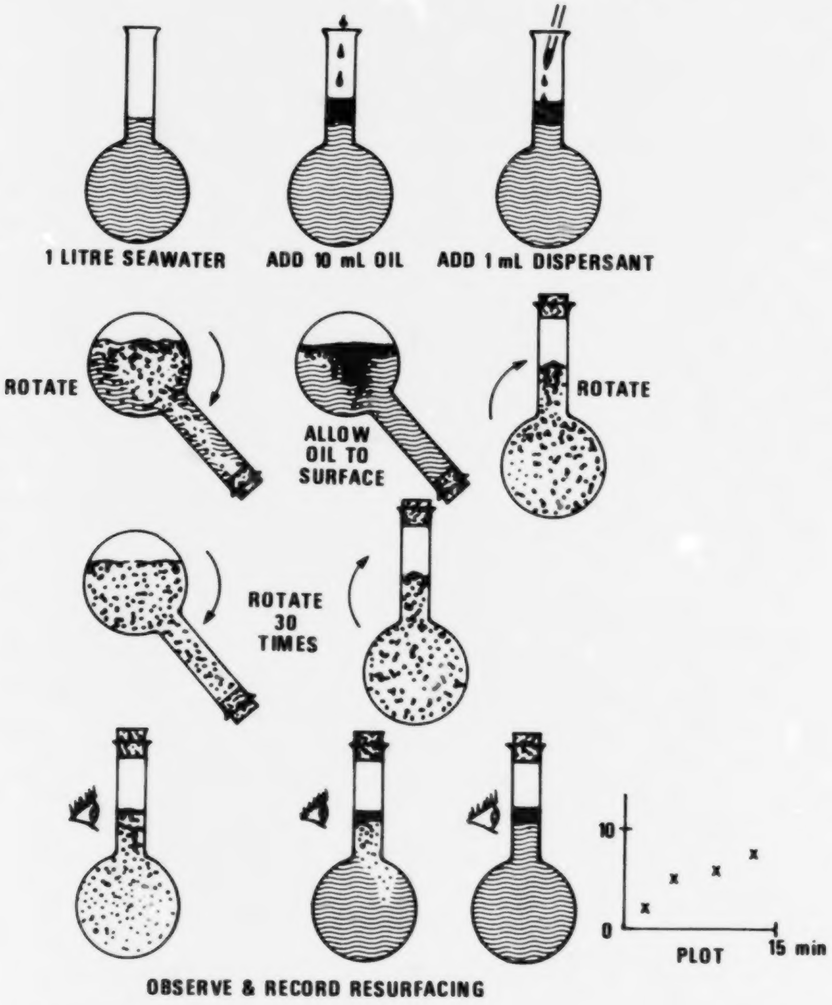

FIGURE 1 ILLUSTRATION OF TEST PROCEDURE

## CONCLUSIONS

We conclude by suggesting that the role of dispersants as a countermeasure in Arctic waters is not yet clear. For example, the recent Dome, Esso, and Gulf Environmental Impact Statement for the Beaufort Sea was entirely non-commital about the use of dispersants. Perhaps there are two "scepticism barriers" to overcome before the role of dispersants will become clear.

The first "barrier" is that there is yet to be an unequivocal demonstration of effectiveness under realistic cold marine conditions. This can only be done by applying dispersants to oils under closely defined conditions and observing the results quantitatively by measuring oil in the water and remaining on the water surface, and reconciling these results with an overall mass balance. These data can then be related to laboratory tests. Some encouraging results have been obtained in U.S. tests using aircraft application under relatively favourable conditions. The problem of droplet formation and aerial dispersion from aircraft has been largely defined, particularly recently, by Lindblom and Cashion (1983). Perhaps the immediate Canadian objective should be to prove the inherent effectiveness of the newer concentrates using oceanic boat tests or helicopter tests prior to attempting further, more ambitious, fixed-wing aircraft tests. Complementary laboratory testing can then be done.

The second "barrier" is a reluctance to believe that the biological effects of dispersion are "acceptable", however "acceptable" is defined. Considerable progress has been made in quantifying the various evaporation, dispersion, diffusion, oil-water partitioning, and toxicological processes which occur when oil is dispersed. We have recently demonstrated that it is possible to quantify these processes individually and collectively (at least approximately), to permit quantitative toxicity statements to be made (Mackay and Wells, 1983). It is clear that the newer, less toxic, highly effective concentrates will not exert a significant, direct toxic effect, at least on some organisms. The dominant toxicants are likely to be those dissolved hydrocarbons which in total can achieve concentrations which are a significant fraction of their saturation values (as discussed by Bobra elsewhere in these proceedings). Evaporation from the slick and from solution in water plays a strong mitigating role in this regard, as does diffusive dilution.

It is now clear that by deliberately selecting conditions in which evaporation was eliminated, the BIOS exposure conditions were unusually severe (and usually predictable) in terms of concentration of specific hydrocarbons; thus, the toxic and bio-uptake effects can be quantified and related to exposures with much greater confidence than if the regime had involved treatment of a surface slick with its many attendant uncertainties. The BIOS and "Maine" experiments, as described by Blackall and Sergy (1983), Page et al. (1983) and Gilfillan et al. (1983), were thus entirely complementary. In combination, they should greatly advance the state of knowledge of near-shore dispersion.

We may thus be close to quantifying the toxic exposure and even the effects, but the issue of "acceptability" (being largely subjective) is likely to remain contentious. At least such discussions will revolve around numbers rather than vague impact descriptions.

In summary, considerable progress has been made on elucidating the effectiveness of dispersants and their joint toxicology with oil. But we need more carefully designed and executed complementary laboratory and oceanic tests before the scepticism barriers are surmounted, or are proved to be too high to cross.

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# SESSION IV-D COUNTERMEASURES STRATEGIES

## A SPILL RESPONSE SYSTEM FOR BREAKUP

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### BACKGROUND

Last summer, the U.S. Secretary of the Interior made a ruling that would permit offshore drilling in the Beaufort Sea for a period of 10 months. In order to use this extended drilling season, potential operators must be able to demonstrate their capability to recover oil during breakup. This capability represents a significant extension of current technology. This paper proposes to meet this requirement with an oil spill response system consisting of an icebreaking barge powered by two arctic class tugs. The barge and tugs would be equipped with modular recovery devices capable of recovering oil from the surface of ice, from an oil/ice mixture, or from open water. The barge would also support two Archimedean Screw Vehicles (ASV) to recover oil pooled on ice or oil floating in narrow leads. Spill response requirements for this system are determined by environmental conditions and the nature of the spill.

### ENVIRONMENTAL CONDITIONS

The nearshore Alaskan Beaufort Sea is a shoal area. Prudhoe Bay has an average water depth of 7 to 8 feet (2 to 2.4 m). East of Prudhoe Bay, the 7-foot depth curve extends 9 miles (14.5 km) offshore, and west of the bay the water reaches a depth of 7 feet at a distance 4 miles (6 km) offshore, just outside the barrier islands. In Harrison Bay, the 7-foot curve is 3 to 4 miles (5 to 6 km) offshore. This bottom topography requires that a shallow-draft vessel be employed.

Currents, tides, and waves are moderate in the Alaskan Beaufort Sea. Currents depend on local winds and are generally less than 1 knot. Tides range from 0.2 feet (0.1 m) below mean low water to 0.8 feet (0.2 m) above. This tidal range is diminished by the presence of fast ice. Waves in open water range from 1.5 to 2 feet (0.5 to 0.6 m), with an occasional swell of up to 6 feet (1.8 m) when the pack ice is far out to sea. Winds tend to be steady at around 10 knots (5.2 m/s) and may exceed 22 knots (11.3 m/s) three to five days per month.

Ambient air temperatures can be expected to be fairly low in this area, even during breakup. The average air temperature for Barrow is 34°F (1°C) in June and 40°F (4°C) in July. During freezeup, another time of interest, air temperatures are much lower. The average air temperature for Barrow is 16°F (-9°C) in October and 0°F (-18°C) in November. During both spring and fall, visibility is obstructed by snow or fog at least 25% of the time.

Fast ice in the nearshore area is at its maximum thickness in the spring breakup season. The expected range of ice thickness is 4.8 to 5.6 feet (1.5 to 1.7 m) in June and rapidly decreases to an open water situation in July. Breakup generally begins with fast ice melting through from the top down in areas where the outflow of rivers covers the surface of the ice. Elsewhere on the fast ice, the snow melts first, thus reducing the albedo of the surface and accelerating ice melting. The fast ice is soon covered with pools of water. In areas of cracks or leads, the water may rapidly run off the ice. Where there are holes in the ice, the water may develop into rapid-flowing whirlpools. Oil spilled on this ice will tend to follow the same path as the water. The oil may stand on top of water pooled in ice; in areas where the water is moving off the ice, the oil will move with it.

The problems of spill response during late freezeup are also of interest. Late freezeup is defined here as the period of time when ice is too thick to permit the movement of open water vessels (about 3 inches (8 cm) thick) but is not thick enough to permit the movement of men and machinery on its surface (about 2 feet (0.6 m) thick). Offshore Prudhoe Bay ice can be expected to have a thickness of about 1 foot (0.3 m) by the end of October and about 2 feet (0.6 m) by the end of November. The proposed icebreaking barge would be capable of breaking ice up to a thickness of about 20 inches (0.5 m) and therefore would be capable of responding to spills during the late freezeup period. Oil spilled during late freezeup can be expected to be mostly contained by the ice and will float freely to the surface (if it has not become encapsulated in the ice) as the ice is broken by the response vessel.

### SPILL RESPONSE REQUIREMENTS

Based on this brief description of the environmental conditions and spill behaviour during breakup, oil spilled on ice or coming to the surface of ice because of melting will start to move as soon as the melting occurs, which is generally a week or two before the ice actually starts to break up. The point to be made is that vehicles used in the spill response system must be ready to move just as soon as any leads develop at breakup and, ideally, provide a mobile platform to recover oil pooled on ice or washing off ice even before these leads develop.

In considering a list of response vessel alternatives, most can be eliminated immediately. A catamaran would not be strong enough to move in narrow leads and would be quickly immobilized by ice pieces being jammed between its hulls. A tunnel hull ship would have the same problems. It would be difficult to make the tunnel hull ship strong enough to withstand the heavy ice pressures; also, the built-in recovery device would only be effective in open water. Considering other conventional response platform alternatives quickly leads one to the conclusion that the principal vessel of the response system must be an icebreaker. Having reached this decision, the question then becomes whether the vessel should be an icebreaking ship or an icebreaking barge.

The technology for designing icebreaking ships is highly developed now, but there are some important disadvantages in selecting the ship alternative. First, a suitable icebreaking ship would have to be quite large for this application and certainly would be very expensive. Although the icebreaking ship could be designed as a dual purpose response vessel/supply vessel, its utility in the supply function might be somewhat less than that of the barge. Second, icebreaking ships must generally have a fairly deep draft, an undesirable characteristic since the nearshore Beaufort Sea is generally shallow.

This quickly leads to the conclusion that the principal vessel of the spill response system should be an icebreaking barge. This vessel has the advantage of a very shallow draft, and even a selectable draft that depends on the load. It also has an open, uncluttered deck space that can easily be fitted with modular, lift-on spill response equipment. The deck space provides ample area for carrying smaller response platforms, such as an Archimedean Screw Vehicle (ASV). The barge is also an ideal support vessel to use in the nearshore area during the periods of time that it is not being used as a response vessel. Most important, the barge has a large storage capacity for recovered oil, about 2300 BBL at a 5-foot draft and 10,000 BBL at an 8-foot draft. Finally, the technology of design for an icebreaking barge has already been applied in the Alaskan Beaufort Sea: Crowley Maritime is presently operating two of these vessels in the area (Figures 1 and 2). The proposed system could, therefore, be assembled now because the existing barges could be fitted out as test platforms to demonstrate and verify the concepts described in this paper.

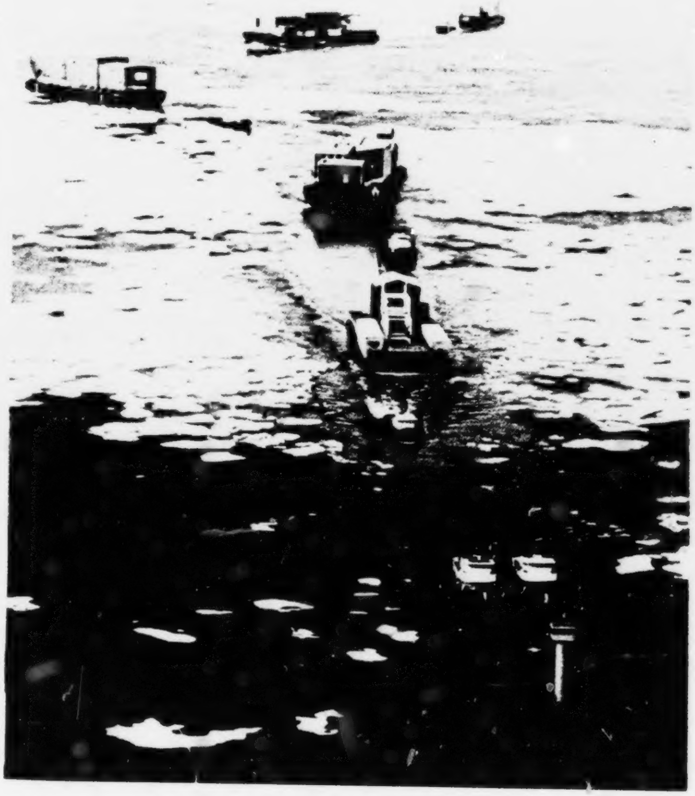


FIGURE 1 "ARCTIC CHALLENGER" LEADING A CONVOY DURING BREAKUP

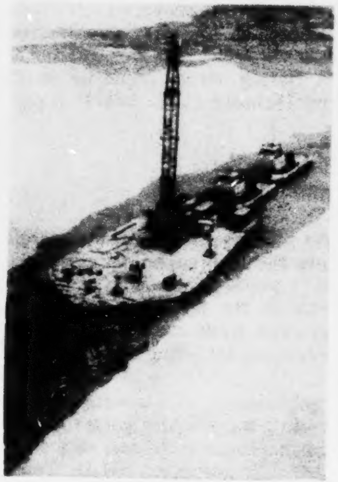


FIGURE 2 "ARCTIC ENDEAVOR" DURING TRIALS IN EARLY FREEZEUP

The support vehicles to be used with the tug-barge combination must also be considered. The principal problem in oil spill recovery during breakup is gaining access to the spilled oil. Oil spilled on or percolating up through ice will collect in melt pools on the ice; if the water on the ice is moving, the oil will move with it into cracks, narrow leads, and holes that are collecting water.

During early breakup, the tug-barge will be frozen in at the pier, unable to move. No conventional icebreaking vessel can be expected to be mobile during early breakup. A conventional icebreaker displaces ice beneath it and/or pushes it aside under the adjacent ice cover as it moves ahead. In the nearshore areas of the North Slope of Alaska, the water is too shallow to permit a ship to move ahead while displacing thick ice. A support vehicle must therefore be used to begin cleanup operations before the barge can move.

The obvious choice of support vehicle for early breakup is an amphibious vessel that can either move over the deteriorating ice or move on and off ice into open water areas or deep pools. A hover barge towed by a helicopter would provide fast response to a spill during this period. It may, however, present a problem as a spill response platform, because the cushion of pressurized air may tend to disperse nearby oil, making it difficult to clean up.

The Archimedean Screw Vehicle (ASV) is also suited to the water/weak ice environment. This amphibious vehicle is well suited to oil cleanup because its catamaran form resembles that of many conventional oil response vessels using continuous strand rope mops between the hulls. The ASV would be highly mobile during breakup because of its ability to move over deteriorating ice, in areas where water has pooled on deteriorating ice, plus on and off ice in open water areas. The disadvantages of the ASV are its relatively slow speed and small carrying capacity. These disadvantages can be offset by using other support systems which will be described later.

The proposed spill response system must be able to retain its mobility in rapidly changing ice conditions to be effective during breakup. To help describe the variations to the proposed system needed to meet these requirements, breakup has been divided into three phases: (a) early breakup, (b) mid-breakup, and (c) late breakup. To cover the broken ice conditions that can be expected in the fall, a fourth ice season, early freezeup, is also considered. The paragraphs that follow describe variations of the proposed spill response system tailored to each of these seasons.

## Early Breakup

A system of ASVs, portable tank sleds, and helicopters has been selected as a response system for early breakup (Figure 3). At the first opportunity after a spill occurred, ASVs equipped with oil skimmers would tow tank sleds towards the spill site; the spill site may be up to 10 to 15 nautical miles offshore. At the same time, a spill response support center would be set up close to the spill site, hopefully on a well-stocked drill island.

The ASVs would go out on the ice and begin collecting oil from the surface as soon as there is melting and pooling of oil. The vehicles would be equipped with rope mop devices mounted between their rotating "hulls". With this configuration they would resemble conventional zero-relative-velocity (ZRV) catamaran skimmers such as ARCAT II, except that the ASV would be able to recover oil pooled on ice, oil on broken ice, or oil in open water. Simple suction pumps could also be used to clean up pools of oil. The ASVs would pull small sled/barges to store the recovered oil. When operating close to the barge or the support base, they could tow the sleds back to transfer the recovered oil. However, the ASV's speed over ice is only about 4 to 6 knots; when operating several miles from the base, large helicopters would be needed to transport the recovered oil. This concept is illustrated in Figure 3. A hover barge towed by a large helicopter could also be used to transport the collected oil (Ocean Industry, 1982).

A flaring burner could be used to dispose of the recovered oil either on the barge or at the spill response support center (Schulze et al., 1982). A portable burner could probably be used at a location where the ice is still hard and stable.

## Mid-Breakup

As soon as sizeable leads permit deployment of the icebreaking barge, helicopters would no longer be needed. Figure 4 shows the icebreaker manoeuvering in an open lead, with rope mop recovery devices deployed over the stern of the tugs. ASVs would continue to use their exceptional mobility to recover oil pooled on the deteriorating ice and also in the open water of the lead. They would return recovered oil to the barge where a mounted crane would lift the full temporary storage sleds onto the deck of the barge for draining. The barge would provide complete support for the recovery operations, including diesel fuel and relief crews for the ASVs.

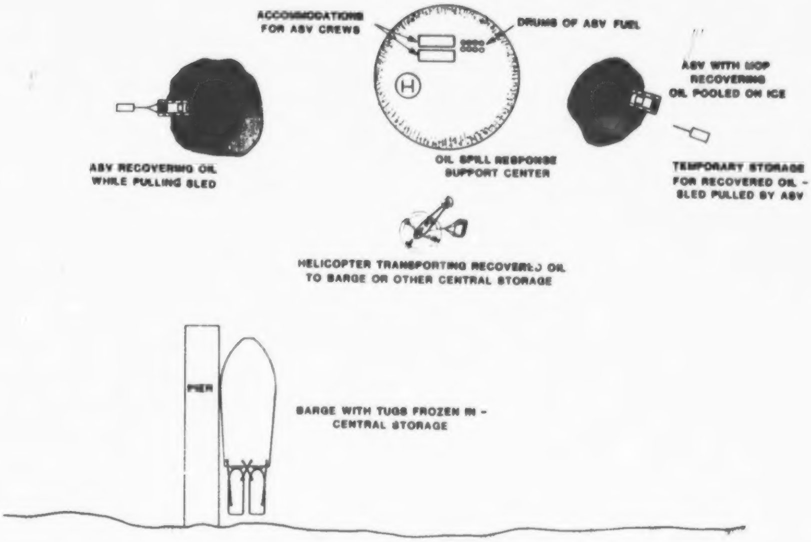

ACCOMMODATIONS FOR ASV CREWS
DRUMS OF ASV FUEL
ASV WITH MOP RECOVERING OIL POOLED ON ICE
ASV RECOVERING OIL WHILE PULLING SLED
OIL SPILL RESPONSE SUPPORT CENTER
TEMPORARY STORAGE FOR RECOVERED OIL - SLED PULLED BY ASV
HELICOPTER TRANSPORTING RECOVERED OIL TO BARGE OR OTHER CENTRAL STORAGE
PIER
BARGE WITH TUGS FROZEN IN - CENTRAL STORAGE

FIGURE 3 SPILL RESPONSE SYSTEM OPERATING EARLY IN BREAKUP

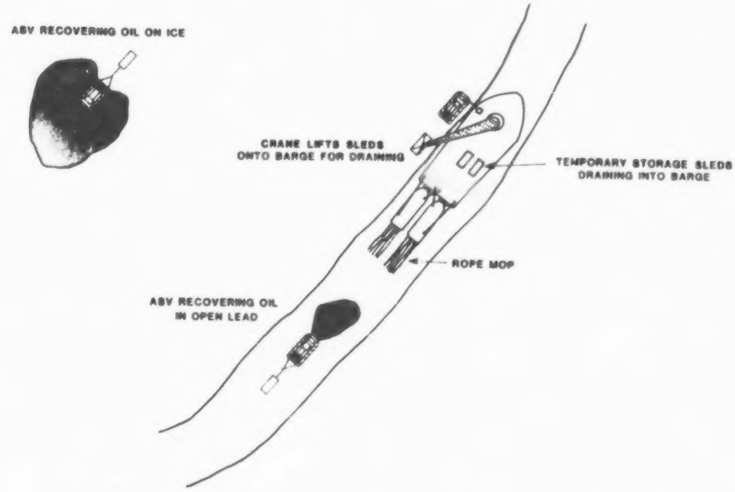

ASV RECOVERING OIL ON ICE
CRANE LIFTS SLEDS ONTO BARGE FOR DRAINING
TEMPORARY STORAGE SLEDS DRAINING INTO BARGE
ROPE MOP
ASV RECOVERING OIL IN OPEN LEAD

FIGURE 4 SPILL RESPONSE SYSTEM OPERATING IN MID-BREAKUP

### Late Breakup

During late breakup, response operations would resemble open water operations. The icebreaking barge would still serve as a base of operations but would also make a larger contribution in recovering oil. Figure 5 shows the barge tugs streaming rope mop skimmers astern as before. But now the barge might also deploy a small containment boom across its bow and use a FRAMO or some other high-volume recovery device to pick up the collected oil. The barge could also deploy rope mop devices mounted abeam. By late breakup, the ARCAT II would begin to have a major role in the recovery operations. The ASVs would clean oil off large ice floes and continue to operate in heavier concentrations of ice.

## Early Freezeup

Normal open water oil spill response vessels will not be able to operate when ice is more than about 3 inches (8 cm) thick. Similarly, when the ice is less than about 20 inches (51 cm) thick, it is too weak to support most heavy land vehicles that might be used for oil spill response. Figure 6 shows how the icebreaking barge would be used for spill cleanup during this period. Three methods are presented. Probably the most effective method would be to open and clean a channel downstream of the spill, recovering the oil as it migrates into the channel. The barge might also simply run through the ice over the spill, then use rope mops deployed from the sterns of the tugs to recover the oil as it resurfaces in the broken channel. Still another method would use the FRAMO oleophilic discs or a heavy oil recovery conveyor belt system deployed from the bow of the barge in the open area created by ramming and backing with the icebreaking barge. The ASVs could also release trapped oil by breaking ice, or they could run upon thicker rafted ice and recover oil pooled in depressions.

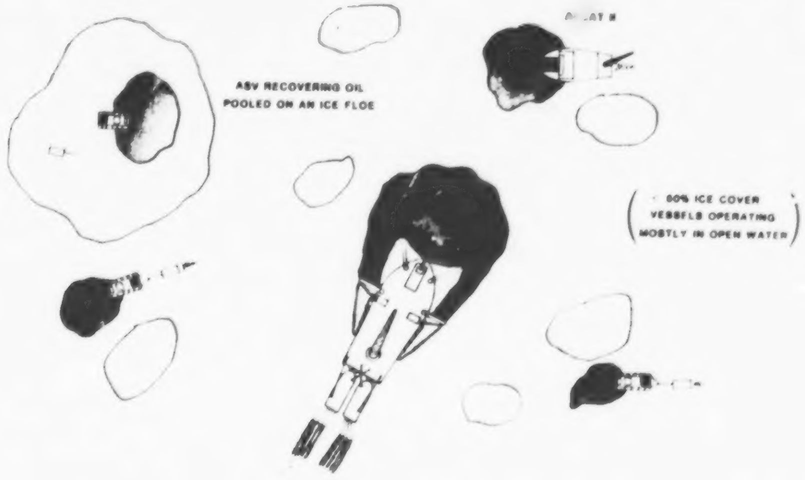

ASV RECOVERING OIL
POOLED ON AN ICE FLOE
80% ICE COVER
VESSELS OPERATING
MOSTLY IN OPEN WATER

FIGURE 5 SPILL RESPONSE SYSTEM OPERATING IN LATE BREAKUP

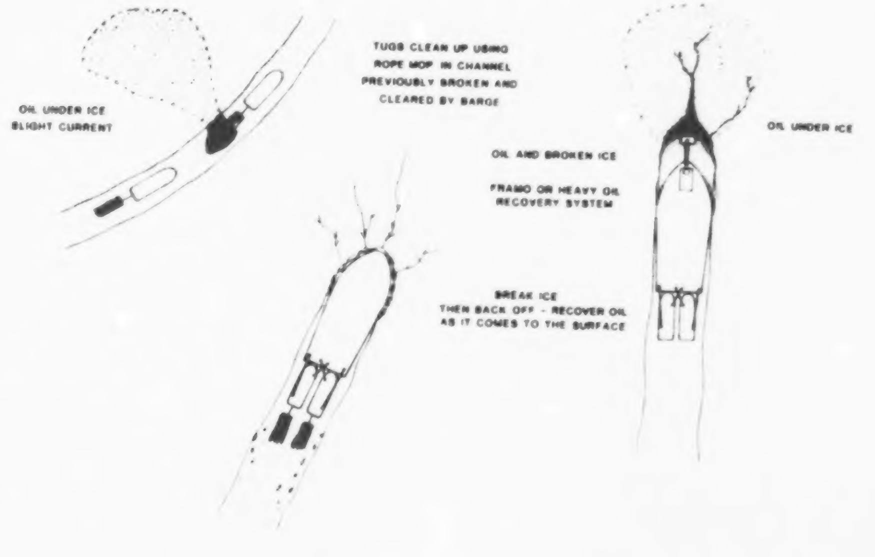

OIL UNDER ICE
SLIGHT CURRENT
TUGS CLEAN UP USING
ROPE MOP IN CHANNEL
PREVIOUSLY BROKEN AND
CLEARED BY BARGE
OIL UNDER ICE
OIL AND BROKEN ICE
FRAMO OR HEAVY OIL
RECOVERY SYSTEM
BREAK ICE
THEN BACK OFF - RECOVER OIL
AS IT COMES TO THE SURFACE

FIGURE 6 EARLY FREEZEUP OPERATIONS

## ICEBREAKING BARGE CONCEPTUAL DESIGN

Icebreaking barges are much too expensive to build and maintain just for spill recovery. Therefore, the object of this design is to outfit a barge, having a primary mission as a deck cargo barge, with "portable" oil spill response equipment. In this sense, "portable" means removable, requiring only minor, if any, structural modifications to the barge. This would eliminate the expense of a dedicated oil recovery vehicle, since the tugs and barge could be used in commercial cargo-carrying service when not needed for spill response. Figure 7 shows a sketch of the barge and tugs outfitted with several devices that have either been tested and proven in simulated arctic conditions (Schulze, 1976), or show the potential of being successful in this environment. The skimming booms shown on the bow of the barge would only be used in open water or away from large concentrations of ice.

The tugs pushing the barge would have accommodations for the ASV crews. The tug crews would operate the cleanup equipment mounted on the barge. Additional accommodations for relief crews could be added to the deck of the barge when required.

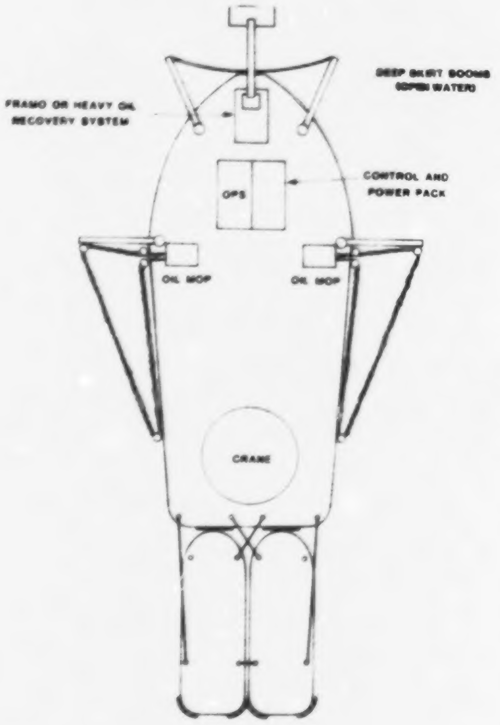

FRAMO OR HEAVY OIL RECOVERY SYSTEM
DEEP SKIRT BOOMS (OPEN WATER)
OPS
CONTROL AND POWER PACK
OIL MOP
OIL MOP
CRANE

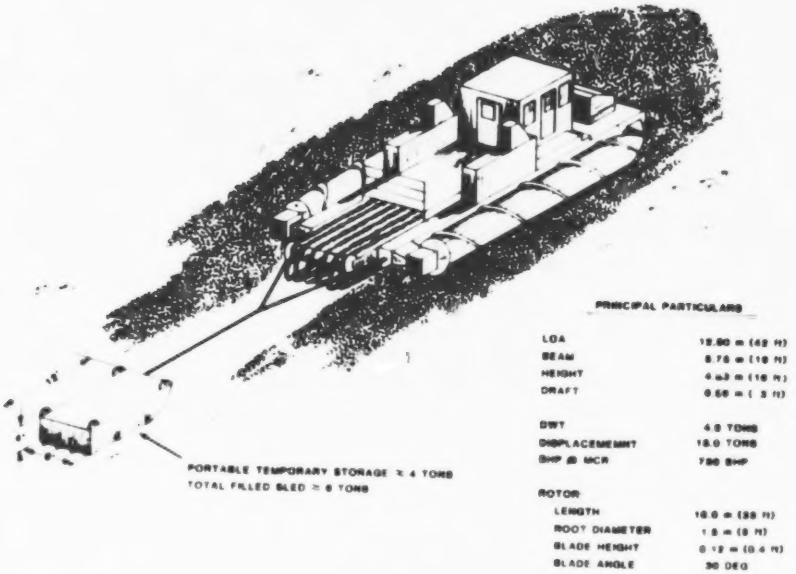
FIGURE 7 RESPONSE EQUIPMENT ARRANGEMENT

## ASV CONCEPTUAL DESIGN

Just as the icebreaking barge is designed as a multi-mission vessel, the ASV is also a general utility amphibious vehicle that can be quickly fitted with a rope mop device for recovering oil.

The oil recovery equipment aboard the ASV is intended to remove oil pooled on ice but will also be able to recover oil from open water and broken ice. Figure 8 shows a sketch of the proposed ASV. This design does not represent a significant departure from existing ASV technology and is essentially the same design as was previously proposed for a sub-arctic area (Schulze and Zahn, 1982).

The proposed recovery system will use two electric motors to transport and extract oil from six 9-inch (23 cm) oleophilic rope mops. These mops travel up over a large diameter roller mounted on the ASV's stern. The rope mops will then run along the deck and under the grating level between the machinery trunks. An idler system will be mounted under the grating to adjust the length of the mops. This adjustment is necessary because the rope mop will be deployed to the bottom of the rotors when the ASV is on ice and to the centerline of the rotors when the ASV is in the water. The rope mops then lead under the deck house and forward to the mop engines.


PORTABLE TEMPORARY STORAGE ≈ 4 TONS
TOTAL FILLED SLED ≈ 6 TONS

| PRINCIPAL PARTICULARS | |
|---|---|
| LOA | 12.80 m (42 ft) |
| BEAM | 5.75 m (19 ft) |
| HEIGHT | 4.83 m (16 ft) |
| DRAFT | 0.60 m ( 2 ft) |
| DWT | 4.0 TONS |
| DISPLACEMENT | 18.0 TONS |
| BHP @ MCR | 750 BHP |
| ROTOR | |
| LENGTH | 10.0 m (33 ft) |
| ROOT DIAMETER | 1.5 m (5 ft) |
| BLADE HEIGHT | 0.12 m (0.4 ft) |
| BLADE ANGLE | 30 DEG |

FIGURE 8 ASV RESPONSE VESSEL

## CONCLUSIONS

This paper suggests that a spill response system that is effective in broken ice conditions can be developed using an icebreaking barge, two pusher tugs, two ASVs, and helicopter support for transporting recovered oil.

The icebreaking barge has the following advantages: non-dedicated service; shallow, variable draft; large storage capability; and a large deck area suitable for deploying many different types of portable modular spill recovery devices.

An ASV is proposed for oil spill cleanup from the surface of ice during breakup because it has: exceptional mobility, particularly the ability to climb from water to ice and from ice to water; a catamaran hull form that lends itself well to proven methods of spill removal; and a direct mechanical means of propulsion over ice that is very efficient, providing a long range on a limited fuel capacity.

The complete response system shows potential for effective spill recovery in a wide range of ice conditions, including all phases of breakup and the broken ice that may occur during freezeup.

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Schulze, R.H., et al., "Oil Spill Response Scenarios for Remote Arctic Environments", U.S. Environmental Protection Agency, EPA-600/52-82-036, Cincinnati, Ohio, (August, 1982).

Schulze, R.H. and P. Zahn, "An Oil Spill Response System for an Offshore Ice Environment", Proc. Fifth AMOP Technical Seminar, pp. 151-176, (June 15-17, 1982).

# EVALUATION OF STRATEGIES FOR OFFSHORE OIL SPILL COMBAT

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## ABSTRACT

A set of system models for supporting decisions in connection with oil pollution contingency plans and executing oil spill combat operations were developed by the Central Institute for Industrial Research, Norway. The approach was based on known decision theories and connected these theories to different methods for oil spill combat, the behaviour of oil in the marine environment, and the damage and costs caused by the spilled oil.

This paper briefly presents the background for the project, the different models used and how they are interconnected, and gives examples of application areas. An analysis made in connection with combat policy is presented. This analysis includes evaluation and comparison of mechanical surface collection near the spill site, protection of vulnerable areas, and use of dispersants. A "bell" or "sombrero" concept for fighting sub-sea blowouts is also analyzed.

## INTRODUCTION

Decisions in the public sector are often complex, involving many conflicting objectives, such as costs and benefits, which often are hard to define, assess and compare, and various types of uncertainties. Nevertheless, decisions have to be made. The political decision system, which in theory shall take into account all aspects of the decision problem, has difficulties in handling complex decisions in a systematic way. To some extent, different types of decision support systems have been introduced, especially where economic policy is concerned. On the other hand, many important decisions (for example, those concerning the level of preparedness against different types of accidents) are still being taken without even trying to systematize the decision process. This very often results in the level of preparedness being decided mainly according to the budget balance, and not according to the goals which are established.

In Norway, the exploration and production of oil and gas on the continental shelf, and the transportation of the produced oil and gas along the Norwegian coast, have significantly increased the possibility of oil spills. As a consequence of the increased risk for an oil spill event and the observed damage caused by spills along the Norwegian coast and other places, contingency plans have been made for handling various types of oil spills on the continental shelf and along the coastline. In order to increase the knowledge on all aspects of oil pollution, a 4-year Oil Pollution Control Research and Development Program (PFO) was started in 1978. Within this program, the Central Institute for Industrial Research (SI) undertook the following project: "Cost/Benefit Analysis of Oil Pollution Control". The goal of this project has been to:

a) give an overall evaluation, with respect to costs and benefits (damage reduction), of both existing and alternative oil pollution contingency plans;

b) develop tools (models, dataprograms) for the future planning of oil pollution combat strategies, both regionally and nationwide.

An important part of the study has been to specify alternative strategies for oil pollution combat. Large resources are required to build up protection against oil pollution damage. The main motivation for this study is to provide governmental agencies and industry with a basis for decision-making: are we on the right "track", or should Norway pursue a different way of handling oil spills.

Our effort is not aimed at automating decisions in this field. We strongly agree with Keeney and Raiffa (1976) that decision problems of this kind cannot be "solved" by sophisticated computer models which, in the end, spill out a "correct result". Any analysis must incorporate an evaluation of risk and value preferences. The ultimate course of action will reflect the trade-offs the society is willing to make between different types of consequences. However, we do believe that a formal evaluation of costs and benefits may help the decision-makers choose a good alternative by providing a rational and systematic procedure for that choice. To ensure that this study can provide a useful tool for decision-making, the work was done in cooperation with both government agencies and oil companies. This has been a great advantage to the project, because it has made available to users the necessary knowledge about the study and how to use the system established in decision making. Alternative strategies were specified and values were given to different parameters describing the various strategies. A more detailed description of the project, the alternative strategies, models and applications is given by Fredrikson et al. (19__).

When discussing and comparing alternatives, it is important to concentrate the formal part of the analysis on differences in various types of costs and damages, to ensure that the analysis is focused on the factors most relevant and important for decision-making. We have chosen to characterize an oil production contingency plan by the following properties: organization; resource level; resource localization; collection and pollution fighting equipment; combat policy. These five characteristics are not independent, and perhaps not even conclusive. Each characteristic is described by different parameters which have to be given a value (or set of values) when assessing various strategies. The characteristics and their parameters are intended to help in concentrating on differences between preparedness alternatives, and give a systematic and quantitative description of their differences. The above-mentioned properties will not be described in detail.

"Organization" describes the way the preparedness is organized, and who has the responsibility to respond on different spills and to supervise both the preparedness and actions. "Resource level" defines the amount of oil combat equipment. "Resource localization" gives information on the storage location of the equipment along the coast. "Collection and pollution fighting equipment" is comprised of different types of equipment (light and heavy booms and skimmers, dispersants, sinking agents, etc.), the uses of which can be combined in many ways. "Combat policy" helps determine the course of action. A large number of different options to choose from are available (for instance, collecting the oil at sea by mechanical means, protecting vulnerable parts of the shoreline, using dispersants as the main measure, directing combat efforts, and planning toward the most frequent types of spill, etc.)

## METHOD

Our basic approach is adapted from decision analyses (Keeney and Raiffa, 1976). We have not aimed at giving an "optimal" or "correct" way of handling the oil spill problem. In our opinion, it is almost impossible to find an objective answer to the question about the best strategy. An answer will always reflect society's preferences (or, in practice, the preferences of the persons who make decisions on behalf of society), towards exploration, production and transportation of oil, the benefit of consuming oil products, and the potential damage of oil spills. Nor is it possible to give absolute answers about future risks of oil spills, potential damage, or potential damage reduction when using collection and pollution fighting equipment, etc.

Our approach to the problem incorporates:

a) assessment of the potential risks involved: frequency, size, duration, location, etc., of future oil spills;

b) consequence models of what happens to the oil, given that a specific spill has occurred and a specific combat action is launched;

c) computation of both preparedness and combat costs;

d) assessment of the economic and various types of environmental damage from an oil spill;

e) a formal method for comparing the different types of damage, and for evaluating the value and risk preferences of the decision-makers.

f) computation of the effect of the uncertainties involved, both in the data input and the models.

The different models that have been developed and used in the analyses are depicted in Figure 1. The figure also shows how an analysis of preparedness alternatives is carried out and how the different parts of the study are linked together. The different models are described in the following sections.

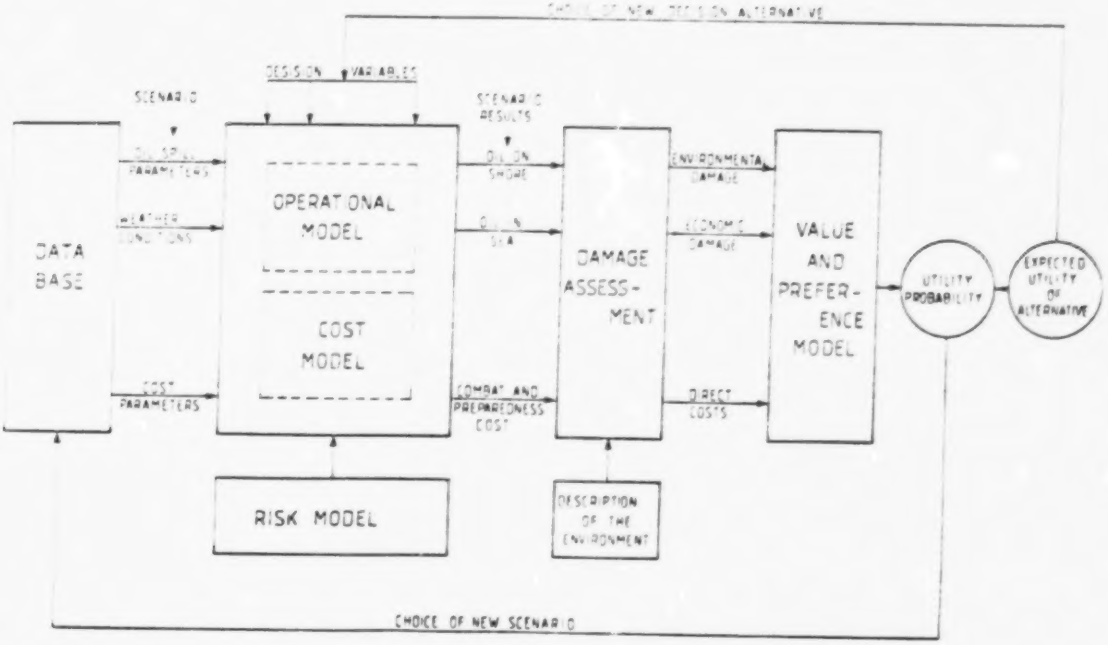
CHOICE OF NEW DECISION ALTERNATIVE
DECISION VARIABLES
SCENARIO
SCENARIO RESULTS
DATA BASE
OIL SPILL PARAMETERS
WEATHER CONDITIONS
COST PARAMETERS
OPERATIONAL MODEL
COST MODEL
OIL ON SHORE
OIL IN SEA
COMBAT AND PREPAREDNESS COST
DAMAGE ASSESS-MENT
ENVIRONMENTAL DAMAGE
ECONOMIC DAMAGE
DIRECT COSTS
VALUE AND PREFER-ENCE MODEL
UTILITY PROBABILITY
EXPECTED UTILITY OF ALTERNATIVE
RISK MODEL
DESCRIPTION OF THE ENVIRONMENT
CHOICE OF NEW SCENARIO

FIGURE 1 ANALYSIS OF OIL POLLUTION PREPAREDNESS ALTERNATIVES

### Operational Model

The operational model is a collection of submodels computing the fate of the oil spill. Four groups of parameters describe the spill:

a) environmental parameters (season, weather development during the spill, ability to operate at night);

b) location parameters (distance from shore, etc.);

c) spill parameters (oil type, oil spill rate and duration);

d) action parameters (when different types of equipment are put into and taken out of action, the expected efficiency of the organization, storage capacity offshore, etc.).

Most of these parameters are given a value exogenously. Some, however, are calculated in the model if their value is not defined in advance. The values of the different parameters are established by the user of the model (or the decision-maker) after discussion with experts. The model computes the following quantities: evaporated oil, naturally dispersed oil, chemically dispersed oil, oil collected at sea, and stranded oil.

### Cost Calculations

The total costs of oil pollution combat are naturally divided into preparedness and operational costs. Preparedness cost includes all permanent economic commitments, and is independent of the number and extent of oil pollution combats. Operational cost includes all costs incurred during an oil combat operation. The main cost elements considered are: organizational costs (administration, personnel, training in spill combat, various rental agreements, etc.); equipments costs (booms, skimmers, ships, dispersants, pumps, beach cleaning equipment, repair); and location costs (storage, supervision, etc.). When appointing values to the different cost elements, we have tried to find the opportunity cost of each element.

### Damage Assessment

The amount of oil collected at sea or prevented from reaching the coastal area may be used as a crude measure of the benefit, or averted damage, of an oil pollution control alternative. Unfortunately, the damage reduction of an oil pollution combat will, as a main rule, not be proportional to the amount of oil collected. Neither will the amount of stranded oil be proportional to the total damage to the shoreline. This makes it necessary to describe and assess the actual damage, both to the environment and economic resources, from a specific oil spill. This is perhaps the most important and most difficult part of any analysis of this type. Various approaches have been made in the project, the most promising of which was computation or estimation of damage measured by the following parameters:

- shore restitution time (years),
- shore length affected (km),
- bird deaths (No. of),
- restitution time for gulls (years),
- restitution time for ducks (years),
- restitution time for auks (years),
- naturally dispersed oil (tons),
- chemically dispersed oil (tons),
- recreational damage (No. of people x days),
- industrial damage (NOK) (all types of economic damage except fishery),
- damage to fishery (NOK).

We have tried to select damage categories that are objectively measurable, give a complete description of the damage incurred, and can be predicted for a given oil spill incident and combat action. Although absolute values may be questionable for many actual oil spills, we believe that the differences in damage measures for oil spill combat alternatives may be reliable figures.

The operational cost and damage models are implemented on a computer (NORD-500). The language used is FORTRAN. It is very difficult, maybe impossible, to develop a damage assessment computer model which evaluates the damage that is acceptable. The damage assessment is therefore carried out both by the use of the computer model and by a group of experts. Kveseth et al. (1983) describe, in more detail, the damage assessment and the value preference model.

### Value Preference Model

Considering the damage categories defined above, a natural question arises: "How to measure the total damage resulting from an oil spill?" If this is necessary for the ranking of oil spill combat alternatives, a comparison between the different damage categories must be made. After considering different approaches, we found the concept of multi-attribute utility theory to be the most promising (Keeney and Raiffa, 1976).

We have chosen a hierarchical structure for the utility function (Figure 2) to make it possible to work with its parts separately. This is especially useful because some parts of the structure seem to be less controversial and therefore more stable than others, where trade-offs between economic and environmental objectives are involved. Thus, it was possible to keep parts of the function unchanged while others could reflect different political opinions.

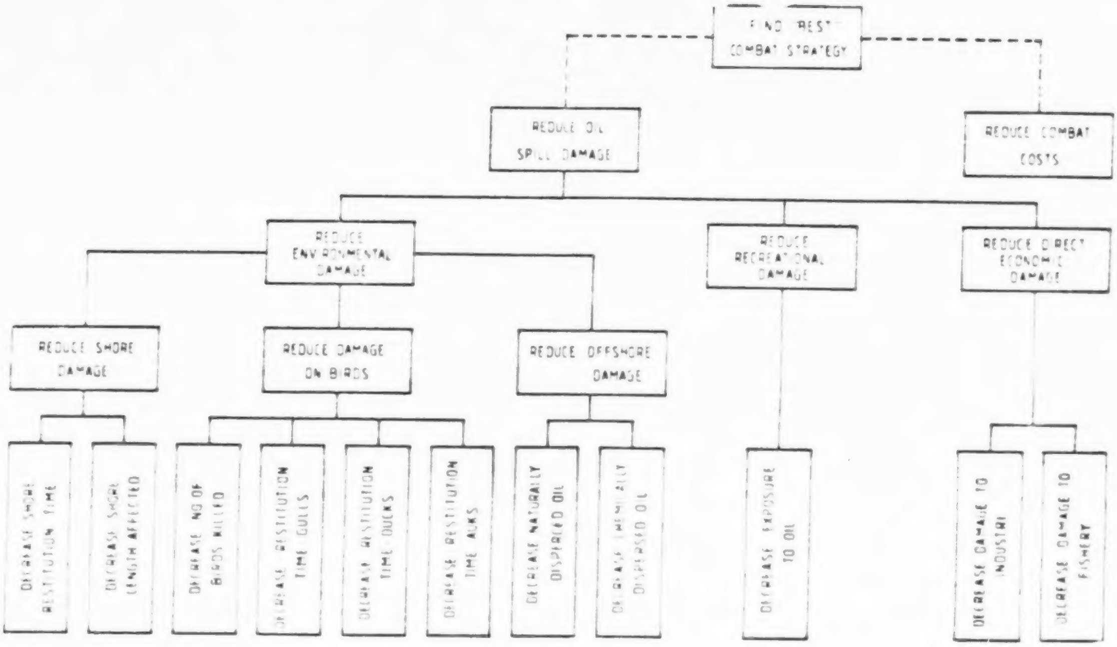
FIND BEST COMBAT STRATEGY
REDUCE OIL SPILL DAMAGE
REDUCE COMBAT COSTS
REDUCE ENVIRONMENTAL DAMAGE
REDUCE RECREATIONAL DAMAGE
REDUCE DIRECT ECONOMIC DAMAGE
REDUCE SHORE DAMAGE
REDUCE DAMAGE ON BIRDS
REDUCE OFFSHORE DAMAGE
DECREASE SHORE RESTITUTION TIME
DECREASE SHORE LENGTH AFFECTED
DECREASE NO OF BIRDS KILLED
DECREASE RESTITUTION TIME GULLS
DECREASE RESTITUTION TIME DUCKS
DECREASE RESTITUTION TIME AUKS
DECREASE NATURALLY DISPERSED OIL
DECREASE CHEMICALLY DISPERSED OIL
DECREASE EXPOSURE TO OIL
DECREASE DAMAGE TO INDUSTRI
DECREASE DAMAGE TO FISHERY

FIGURE 2 STRUCTURE OF THE VALUE MODEL

The utility function is supposed to reflect the "true" preferences of the "decision-maker". Since the concept of a decision-maker is not well defined in this context, our main concern was that the structure of the function should be reasonable, whereas its content should adapt to different sets of preferences (Keeney and Raiffa, 1976; Fredrikson et al., 1983).

Given a specific oil spill and a combat action, the operational, cost, and damage models compute the various (objective) consequences of the spill. The resulting measure of the combat alternative is its utility (a number between 0 and 1), which express the ability of the combat action to limit the total damage of the spill. The utility number may also be transformed into an economic measure, the value of the action, which expresses our willingness to pay for the action.

When it comes to identifying utility functions, our policy has been to let different groups work out functions independently. This is done with the help of the interactive APL-program package UTILIT (Fredrikson et al., 19__) which was developed at the Norwegian School of Management. A convenient way to check whether the functions agree with the real preferences of the groups is to confront them with the resulting willingness to pay for various well-described artificial or actual scenarios. A supplementary method is to cross-compare the different functions in plenary sessions. This is facilitated by the hierarchical structure of the total function. We then try to decide which differences are due to randomness or uncertainty and which reflect real differences of opinion.

### Risk Model

Risk is a main variable when deciding the level of preparedness against different types of accidents. It is, however, impossible to make accurate forecasts about the future rate of accidents. In this project, we have used historical data on the rate of tanker accidents near the Norwegian coast to forecast the future. We are aware that the accident rate is a stochastic event which is dependent upon the rate of transportation, regulations, education of the crew, etc. This is taken into account in the uncertainty analysis. When calculating the risk of blowout from drilling and production activities, we have used data from the North Sea and other areas, and forecasts of the level of activity offshore in the North Sea basin and along the northern part of the Norwegian coast.

By using some of the state variables describing a possible oil spill (a scenario), it has been possible to establish probability trees giving the probabilities of different scenarios. The state variables used in connection with oil spills from tankers are weather, location, type of oil and amount of oil spilled. Even though we have used an aggregate description of the scenarios, we have identified more than 600 different scenarios. By analyzing and comparing different scenarios, it has been possible to significantly reduce the number of scenarios which have to be studied in detail.

### Uncertainty Analysis

Uncertainties both in the estimates of different state parameters and in modelling are unavoidable factors that must be considered when this type of decision analysis is carried through. The most important type of uncertainty in this analysis are the risk parameters (frequency, size, duration, localization, etc.) of a future oil spill. In addition, the modelling, the estimation of the effect of combat actions and various damage consequences of the released oil, and the comparison between damage preparedness and combat costs incorporate uncertainties that cannot be neglected in a decision analysis. A systematic way of dealing with these uncertainties has been developed (Fredrikson et al., 19__).

## EXAMPLES OF APPLICATION

The set of models described previously has been used to study different strategic and tactical decisions (Fredrikson et al., 19__). Strategic decisions are also described. Tactical decisions are made in response to a specific oil spill, for example:

a) what should the recovery capability be in order to respond to the spill?

b) what are the response times (equipment and crew)?

c) which type of equipment should be used?

We will briefly present some of the results from an analysis made in connection with combat policy and an analysis of a sombrero concept for fighting sub-sea blowouts. Both analyses will be described in more detail in the oral presentation of the paper. Besides these analyses, organization on strategic levels and different collection and pollution fighting equipment have been analyzed. It must be made clear that these analyses are not complete and were made under limited cost-margins.

### Analysis of Combat Policy

The basis for the analysis was that an oil pollution contingency plan should exist. Three different combat policies were evaluated: mechanical surface collection near the spill site; production of vulnerable areas; and use of dispersants.

**Mechanical Surface Collection Near the Spill Site.** Mechanical collection with booms and skimmers near the spill site is the accepted approach to fight oil spills on the Norwegian continental shelf. The efficiency of this method is highly sensitive to such parameters as:

- weather condition (wind and waves);
- availability of resources (collection equipment, storage capacity of collected oil);
- professionalism of the combat team, and the manpower needed to sustain a continuous operation over a long period of time;
- safe distance from spill site;
- oil emulsification before collection and viscosity of oil;
- ability to operate efficiently at night.

The main reason for surface collection near the spill site is the high oil concentration in a limited area. Also, the amount of water in the oil-water emulsion is relatively low. However, the constraints are many and they have great influence on the collection efficiency.

**Protection of Vulnerable Areas.** An alternative approach to offshore oil spill combat is to activate the oil spill combat action when the oil threatens the shoreline. As the wind and the current continue to bring oil to the coast, oil will accumulate and may reach high concentrations. Off the coast, the oil slicks will be thin and patchy, and collection efficiency will be very low. (This situation may be significantly different from cases of a large spill occurring over a short period of time). The oil tends to move parallel to land until trapped in an eddy-current or a bay. Many such locations where oil accumulates naturally can be expected to occur. It will sometimes be possible to use booms to guide the oil into these natural traps. The purpose of this combat action is to protect vulnerable areas and to steer as much of the oil as possible into selected areas. The main activity is then to recover the oil from these areas to prevent it from drifting out again and spreading the pollution. When the influx of oil stops, the oil may be fenced in with booms until it can be collected.

In principle, the same types of equipment and resources are needed as in the case with offshore collection. In practice, the requirements to the equipment will change due to the differences in offshore and inshore operations. To follow this combat policy means that less oil will be collected at sea, and more oil will threaten the shoreline. The damage inflicted by the oil will, however, most likely be less than with an offshore operation, because the main combat effort is directed towards protection of sensitive shoreline areas.

If the resources are limited, one has to selectively protect the most vulnerable and valuable areas. On the basis of actual weather conditions and knowledge about currents, one must also select different bays as traps into which the oil can be guided.

**Use of Chemical Dispersants.** Many countries have been reluctant to use chemical dispersion of oil. This may partly be due to damage caused by dispersants used after the TORREY CANYON accident, though it has been claimed that there were no observable effects on fisheries. The only significant, well-documented damages from oil spills have occurred when the oil came close to land or drifted ashore. Some seabirds are very vulnerable and are of major concern. Furthermore, damage to shores, property, coastal fisheries, etc., must be considered.

If the oil can be dispersed successfully or recovered before reaching the shore or an area inhabited by seabirds, these damages can be prevented. The ecological trade-off for dispersing the oil in open areas is some damage occurring to plankton and other organisms in the affected water volume. Possible long-term effects are of particular concern (Fredrikson et al., 19__). However, simple calculations as well as observations show that highly concentrated dispersions of oil will affect small volumes of water and only for a short time. The toxicity of the dispersants now in use is low compared to those used after the TORREY CANYON accident. In general, dispersion of oil will probably do little harm in open areas.

In addition to the reduced size of the oil film on the surface, arguments for the use of dispersants include the following:

- less water-in-oil emulsion or tarballs will be formed. Tarballs may be a nuisance when drifting ashore;
- the increased surface area of the oil particles increases the rate of biodegradation;
- the oil has less tendency to stick to particles or other surfaces.

Most of the objections to using dispersants seem to be valid only in shallow water close to the shore, where water exchange is poor; higher concentrations may persist for longer periods and may possibly approach values known to cause observable effects in laboratory experiments (Fredrikson et al., 19__). Great caution should also be exercised when using dispersants in an area with a high density of fish eggs and larvae, even in open waters. It is not known if this may increase the mortality of the eggs and larvae.

Dispersants are more effective for low viscosity oil, and rapid reaction after a spill is important. If the oil has been on the water a few hours, the efficiency of dispersants is severely reduced. Laboratory tests show a high efficiency of many dispersants. Experiments carried out at sea under realistic conditions show rather variable results. High efficiency has been reported when concentrated dispersants have been spread from aircrafts. Norwegian studies with Statfjord crude oil showed an efficiency of about 20% for two dispersants, while a third had little effect. The effectiveness could probably be increased by using a better spraying procedure.

### Main Conclusions

Even under "good" weather conditions (wave-height 0.5-1.5 m, wind speed 4-8 m/s), most likely not more than 15-20% of the oil will be collected (with existing technology). The subsequent reduction in stranded oil (measured in tons) will be less, since much of the oil recovered near the spill site otherwise would have evaporated or dispersed naturally (especially if the spill is far off the coast). The analysis shows that the damage reduction of an offshore combat operation, based on mechanical collection, is an order of magnitude less than the corresponding combat costs.

The analysis indicates that a combat action based on the protection of sensitive areas by guiding the oil into traps may significantly increase the willingness to pay for the combat action, when compared to offshore collection. Also, the response time requirements may be relaxed for this combat policy, thereby decreasing the overall costs to an oil spill contingency.

The analysis indicates that the use of dispersants, at least in open sea areas, could increase the total benefit from the combat action. The argument is partly that it has become more and more evident that mechanical collection of oil on the ocean and in exposed coastal waters suffers from severe limitations. Mechanical collection of oil in open seas is only possible under good weather conditions. Though this may also be the case for dispersants, the dependence on good weather conditions does not seem to be as critical as for mechanical collection. Furthermore, Norwegian oil is rich in light components and therefore of low viscosity. This is a drawback for mechanical collection; chemical dispersants, however, may be of higher efficiency.

The best combat policy will probably be a combination of mechanical recovery, use of dispersants, and protection of vulnerable areas. For a combat policy including all these actions to give good results, distinct directives for when, where and how to use each action must be established.

### An Analysis of a "Sombrero" and a "Bell" Concept

The methodology and models are also used to evaluate the cost efficiency of underwater collection devices (bell, sombrero) compared to conventional strategies (booms and skimmers, dispersants). The study concentrates on the damage potential of a large underwater blowout; no technicalities of the concepts are discussed. The conclusion is that the damage from such a blowout can be substantial both with respect to ocean fishery and coastal environment. An underwater collection/device has to prove a high degree of efficiency (>60%) to be interesting (Østby and Westergaard, 19__).

## FINAL REMARKS

The cost/benefit-decision analysis approach aims at utilizing results and models from many different areas: economy, oil drift models, oil collection technology, ecology, effect of pollution in the marine environment, organization, etc. We believe that this type of interdisciplinary effort is necessary when complex and important social problems are studied, especially when decisions have to be made in an environment of conflicting interests and when result measures are hard to compare.

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# COUNTERMEASURES FOR A MAJOR OIL SPILL FROM A TANKER IN ARCTIC WATERS

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## INTRODUCTION

The search for energy reserves, both natural gas and oil, in the Arctic has experienced rapid growth since the 1970s. This activity has located supplies of both oil and gas which show economic promise; systems are being developed to move these resources to market.

Oil has been found in the southern Beaufort Sea; one of the principal developers, Dome Petroleum, is currently designing large icebreaking tankers to ship product to eastern markets via the Northwest Passage.

In addition, gas reserves have been found in the western high Arctic at Melville Island. Plans are underway by Petro-Canada and others to construct large icebreaking liquid natural gas carriers to transport this fuel to the east coast, again through the Northwest Passage.

While other projects in the North are not as advanced in their planning with regard to the use of the Arctic as a shipping zone, such endeavours are expected in the future. The American oil development in Alaska has considered the use of this tanker route to supplement its existing pipeline flow which is presently near capacity. Exploratory drilling for oil in several parts of the Canadian Arctic is also actively being pursued. Shipment of these commercial resources could be accomplished by large Arctic Class vessels.

The advent of year-round shipping in the North creates the potential for accidents and the release of hydrocarbons into the environment. Of primary concern is the transport of crude oils by tanker.

This paper presents a review of techniques available to respond to a major oil spill from a tanker in Canadian Arctic waters. The size of potential oil releases and the behaviour of the spilled oil in a range of Arctic environmental conditions are discussed. Also included is a survey of the applicability of conventional countermeasures to a northern tanker accident. The use of igniters to burn oil contained by a complete ice cover is analyzed, and potential on-board self-help spill control and cleanup techniques for proposed Arctic tankers are reviewed. Finally, conclusions are drawn regarding the state-of-the-art, and recommended actions are presented.

## ACCIDENT SCENARIOS

A recent study of the risk of oil spills from Arctic tankers travelling along the route indicated in Figure 1 concluded that the Arctic tankers would have a safety factor 120 to 160 times greater than that of a conventional tanker operating on a southern Canadian route (Bercha, 1981). Table 1 shows the distribution of projected Arctic tanker accidents.

TABLE 1 ARCTIC TANKER ACCIDENT TYPES
(adapted from Bercha, 1981)

| Accident Type | Percent of Total |
|---|---|
| Collision | 5.6 |
| Explosion | 0.04 |
| Grounding | 58.8 |
| Iceberg Collision | 0.3 |
| Ramming | 4.4 |
| Structural Failure | 32.4 |
| TOTAL | 100.0 |

Each of the accident types involves a crack or hole in a cargo tank. There are four possible locations where these breaches can occur: above the waterline, at the waterline, in the side below the waterline, and in the bottom. For the purposes of this paper, cargo tank hole sizes of 5, 0.5 and 0.1 $m^2$ were considered. The 5 $m^2$ case represents a worst plausible case in the event of a severe impact or grounding, while the 0.5 and 0.1 $m^2$ cases represent the probable size of cracks in the cargo tank resulting from an accident. Figure 2 illustrates the location of the breach in the cargo tank and the fate of the oil as it leaks out.

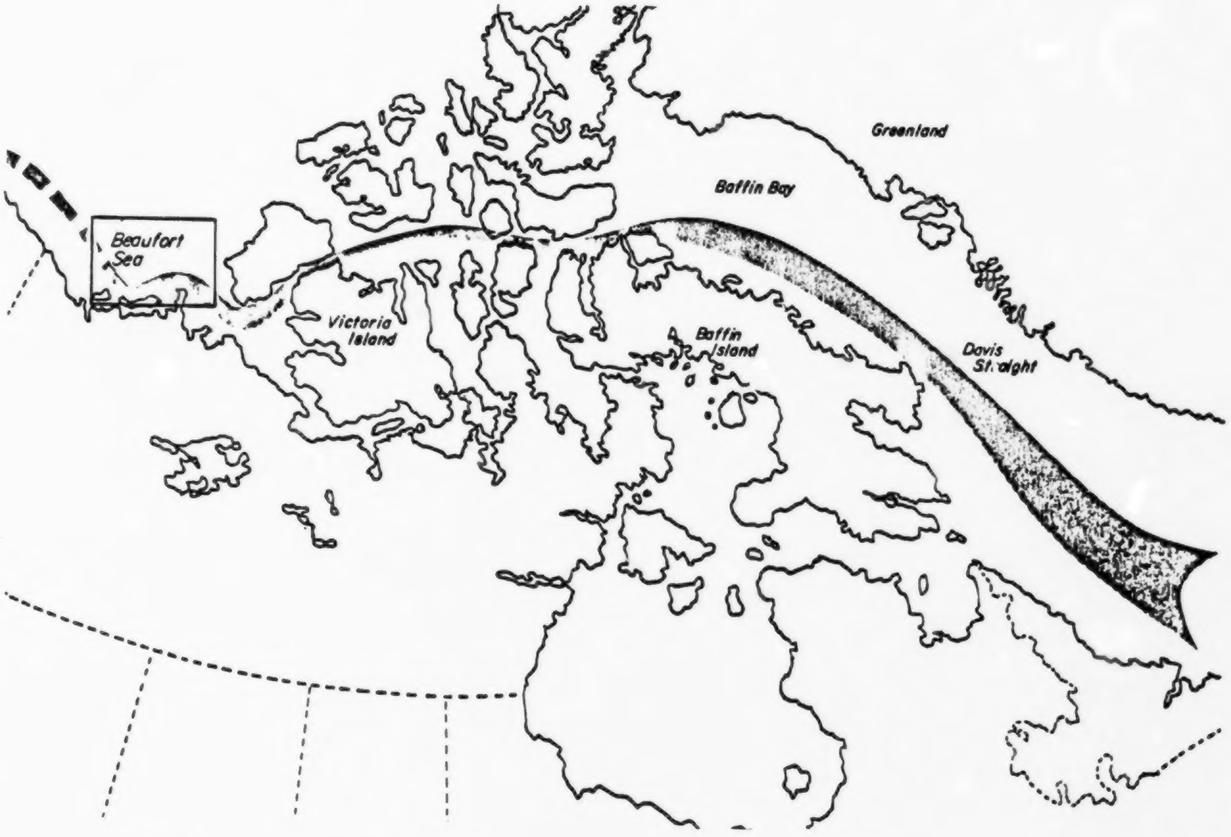


FIGURE 1 PROPOSED ARCTIC TANKER ROUTES

The chosen hole sizes are small in comparison with those recorded for historical tanker accidents. Webb Institute (1974) has shown that about 60% of past conventional tanker collisions resulted in perforations greater than 4 m and that 40% were greater than 6 m (the distance between the inner and outer hulls of the proposed Arctic tankers). They were selected because of the strength of the proposed Arctic tankers and the existence of a double hull. The hull of Dome's proposed tanker is reported to be ten times stronger than that of a conventional tanker in a collision or ramming situation (Bercha, 1981). A U.S. Coast Guard Study (Card, 1975) indicates that a double bottom with the depth of the one proposed for the Arctic tankers would reduce the number of oil spill-related grounding incidents by 90%.

### Oil Outflow

The driving force for oil leakage from a holed tank can be characterized as having two distinct regimes: the pressure difference across the tank wall and the buoyancy of oil in water. The former predominates immediately after the holing of a tank; the latter predominates once the pressure difference across the hole drops below 0.01 $P_{ATM}$ (Dodge et al., 1980). For holes in the tank side below the waterline (Figure 2), water will be ingested into the tank through the hole, driven by the difference in density of oil and water. The process can be viewed as a streamtube of water flowing into the tank, floating the oil up, and resulting in a streamtube of oil flowing out of the tank. The oil and water flows share the area of the hole, with the volumetric inflow of water equalling the volumetric outflow of oil. This process continues until the water levels reaches the top of the puncture.

For holes above the waterline in sealed tanks, air is ingested into the tank when the pressure difference drops to 0.01 $P_{ATM}$; the outflow continues as the ingested air increases the pressure in the ullage space (Figure 2). This continues until the level of the oil drops to the bottom of the puncture. For holes in the bottom, the outflow continues until the pressures are equal inside and outside the tank at the puncture point.

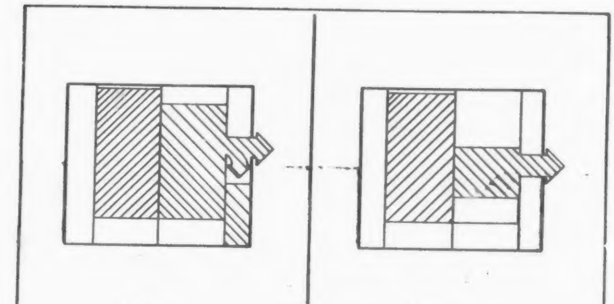


FIGURE 2 POSSIBLE TANK BREACH LOCATIONS AND FATE OF OIL WITH NO COUNTERMEASURES

In terms of total volume of oil lost, the worst case is a hole in the side of the cargo tank at the waterline. In this instance, the entire contents of the tank will be lost.

**Predicted Oil Losses.** The volume of oil lost from a cargo tank as a function of time was calculated for Dome's proposed 200,000 dwt Arctic tanker design (Ross, 1983b). The oil losses were calculated for holes located at, above, and below the water.

Figure 3 shows the results for a waterline hole in a cargo tank of the 200,000 dwt tanker, and Figure 4 presents the oil outflow rate as a function of time. Much of the oil loss occurs in the first few minutes and hours after the accident occurs. The flowrate declines steadily with time until the water ingestion process starts. From this point on, the flowrate is constant until all the oil has escaped.

Figure 5 illustrates the oil loss characteristics of a puncture in a 200,000 dwt tanker 5 m above the waterline. As compared to the case of a hole at the waterline, the total volume of oil lost is considerably reduced since the process of water ingestion does not take place. A large diameter hole releases more oil than a smaller hole, as the oil drains to the bottom of the puncture. The characteristic rapid loss of oil from a large hole compared to the slower loss from smaller holes is evident. The effect of the distance of the hole from the waterline on the total oil volume lost is illustrated in Figure 6.

The trajectory of the oil released from a hole above the waterline can be calculated by comparing the oil discharge velocity with the acceleration of the oil stream due to gravity (Ashworth, 1982). The results of such an analysis (Figure 7) indicate that, providing the wing ballast tank is not flooded, the oil will be contained within the wing tank. The

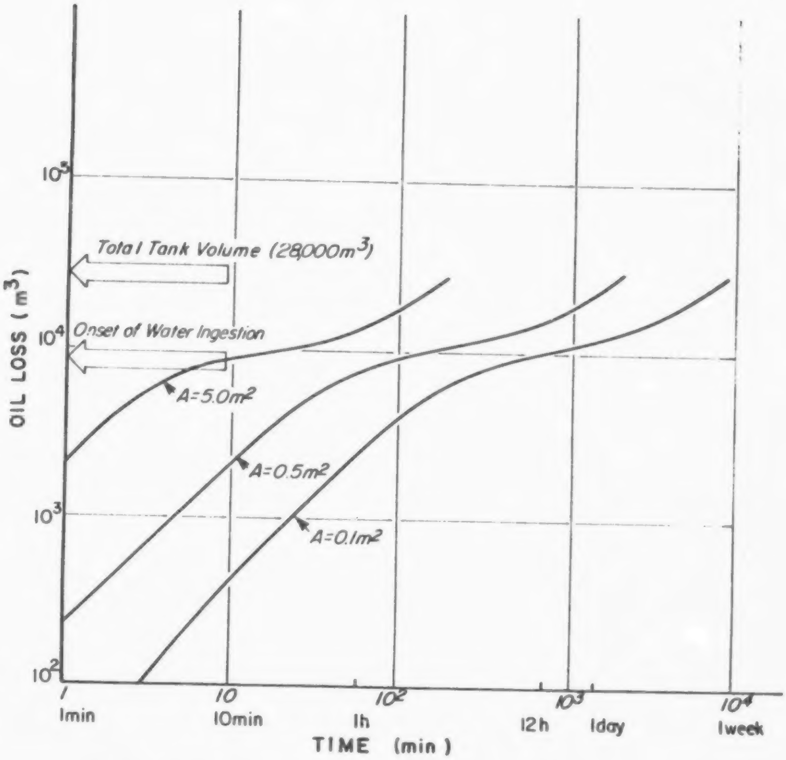


FIGURE 3 OIL RELEASE SCENARIOS FOR A 200,000 DWT TANKER WITH A HOLE AT THE WATERLINE (tank fully vented)

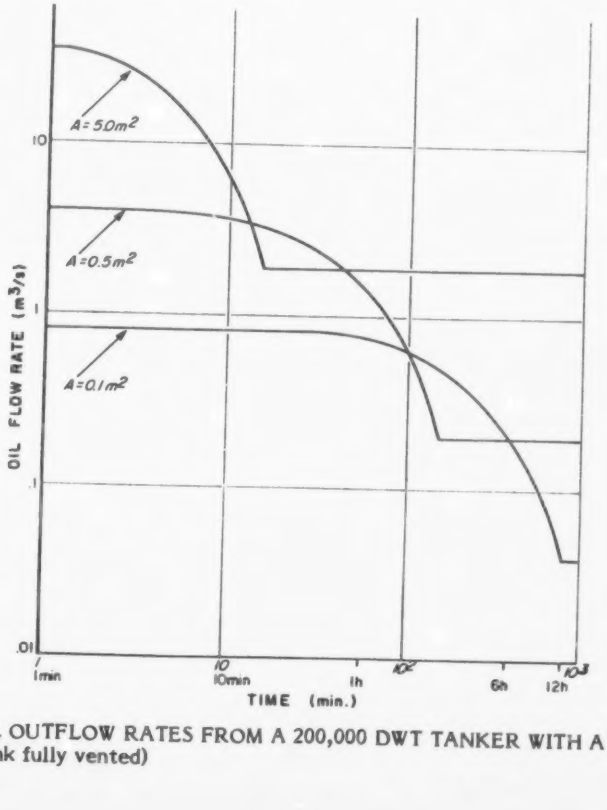


FIGURE 4 OIL OUTFLOW RATES FROM A 200,000 DWT TANKER WITH A HOLE AT THE WATERLINE (tank fully vented)

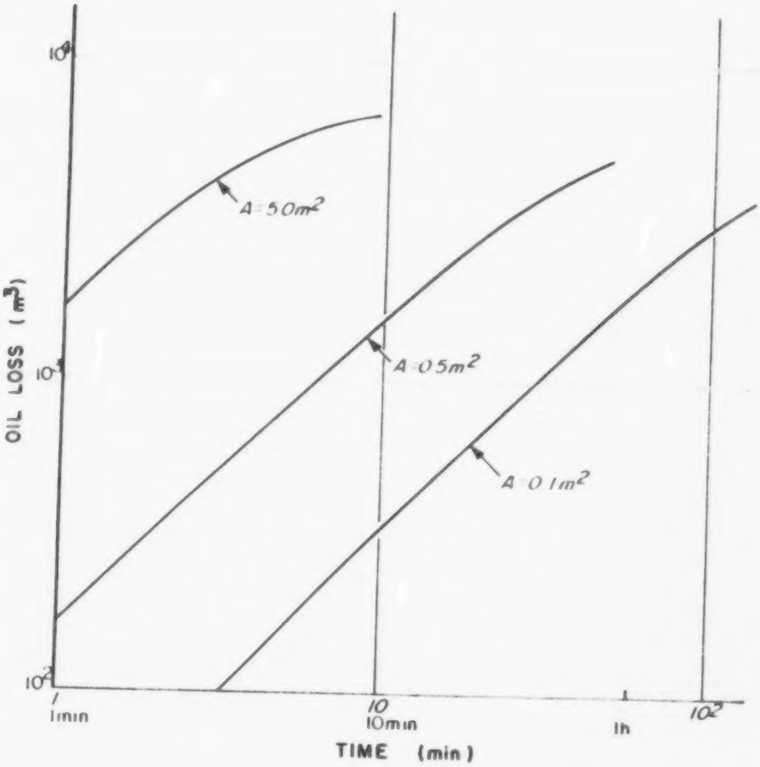


FIGURE 5 OIL RELEASE FROM A 200,000 DWT TANKER PUNCTURED 5 m ABOVE THE WATERLINE (tank fully vented)

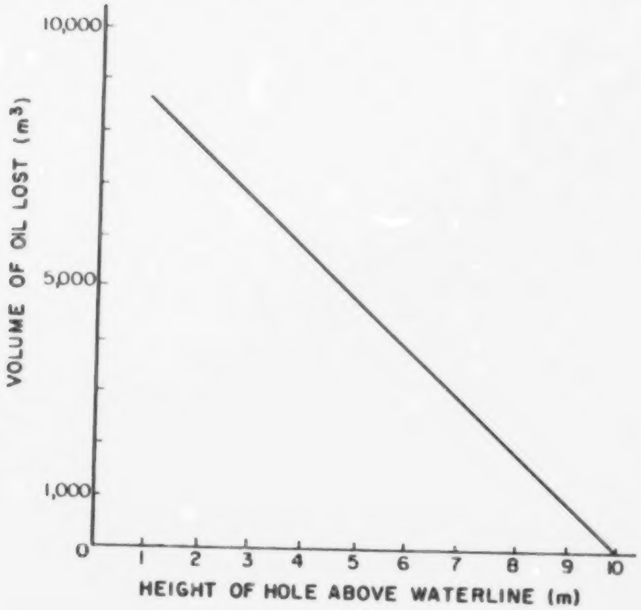


FIGURE 6 EFFECT OF HEIGHT OF HOLE ABOVE WATERLINE FOR A 200,000 DWT TANKER ($A = 0.5\ m^2$, tank fully vented)

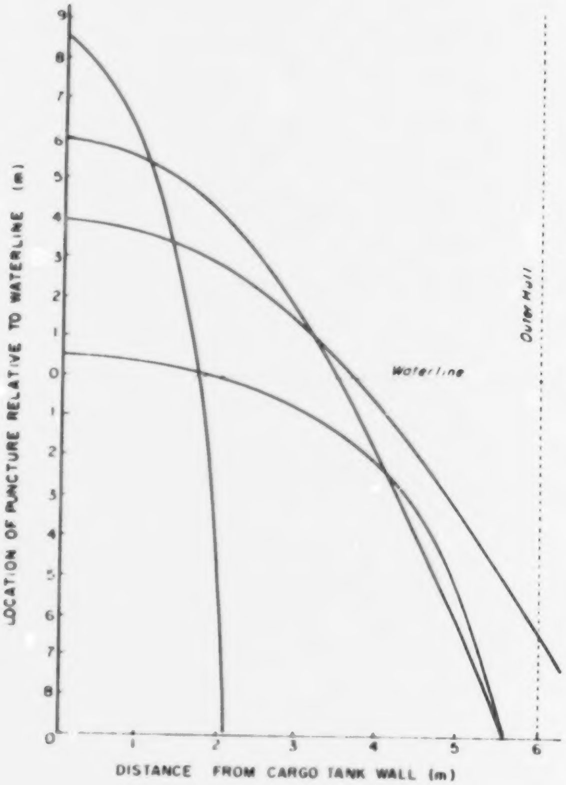


FIGURE 7 INITIAL TRAJECTORY OF ABOVE WATER PUNCTURES (200,000 dwt tanker, tank fully vented)

holding capacity of the wing tank (in excess of 24,000 $m^3$ below the waterline) is more than sufficient to hold the volume of oil released.

Figure 8 shows the effect of the depth of a hole below the waterline on the total volume of oil lost from the tank for the 200,000 dwt tanker. The initial outflow characteristics for a hole below the waterline are almost identical to those of a hole at the waterline (Figure 3). The differences are that water ingestion commences sooner (due to the difference in oil and water density) and ends earlier (the water reaches the top of the hole sooner) in the case of a hole below the waterline. The decreasing volume of oil lost with increasing depth of the hole is due to the volume of oil contained in the tank between the equilibrium oil height and the top of the hole.

Also shown on Figure 8 is the holding capacity of the wing tank. If the cargo tank is punctured, the oil will first displace the water in the upper portion of the flooded wing tank. Once the level of oil in the wing tank reaches the level of the hole in the outer hull, it will begin to leak from there to the sea (Figure 2 (C)). Only for holes between the waterline and about 10 m depth will oil be released to sea.

A hole in the bottom of a cargo tank would release some 6,400 $m^3$ of oil (Figure 8). Based on the results of scale-model tests done for Dome Petroleum (Arctic Offshore Design Ltd., undated), 5,600 $m^3$ (87.5%) of this oil would be released to the sea and 800 $m^3$ would be retained in the double bottom (Figure 2 (D)). The initial outflow rates would essentially be identical to those for the case of a waterline puncture.

### Environmental Conditions

The proposed route for the tankers through the Canadian Arctic from the Beaufort Sea to eastern markets is depicted in Figure 1. Since the tankers are to be designed for year-round use, a wide range of environmental conditions must be considered when evaluating oil spill countermeasures. In this study, four sets of environmental conditions have been specified and are delineated in Table 2. The behaviour of the oil released in calm open water, rough open water, complete ice cover, and 6/10ths ice cover with moving floes is also shown.

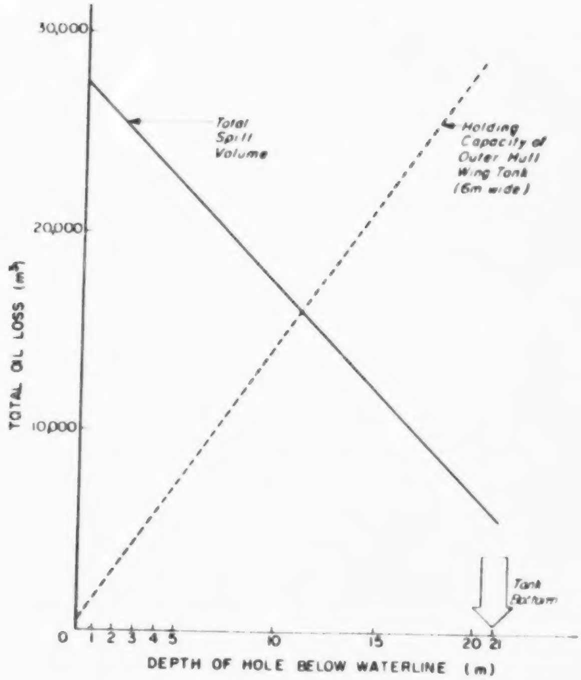


FIGURE 8 EFFECT OF HOLE POSITION BELOW WATERLINE (200,000 dwt tanker, $A = 0.5\ m^2$, tank fully vented)

TABLE 2 ENVIRONMENTAL CONDITIONS (adapted from Ross, 1982)

| Type | Ice | Waves (m) | Currents (m/s) | Water Temp. (°C) | Air Temp. (°C) | Daylight (h) |
|---|---|---|---|---|---|---|
| Open Water - Calm | None | <1.5 | <0.4 | 5 | 5 | 16-21 |
| Open Water - Storm | Bergs | >3 | >1 | 2 | -20 | 6-9 |
| Winter Ice | 6/10 1st year 2 m thick, 4/10 multi-year 3 m thick, 1 ridge/km | None | 0.05 | -1 | -30 | 10 |
| Ice Floes | 6/10 floes up to 5 km dia., 15-25 km/day drift | None | 0.3 | 0 | -10 | 24 |

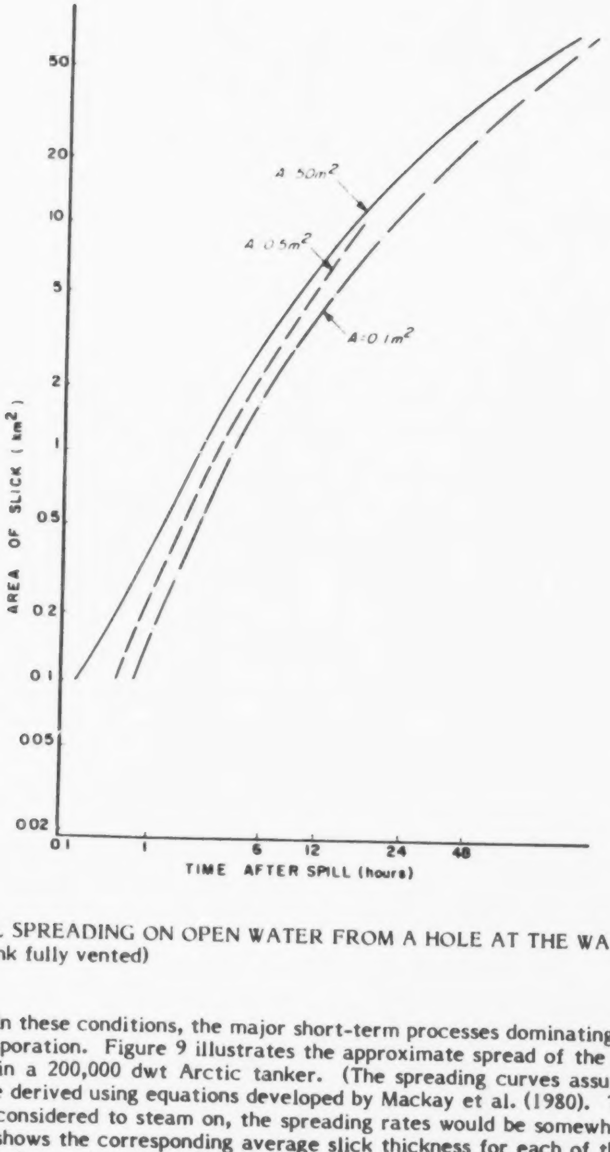


FIGURE 9 OIL SPREADING ON OPEN WATER FROM A HOLE AT THE WATERLINE (tank fully vented)

**Calm Open Water.** In these conditions, the major short-term processes dominating the behaviour of the oil will be spreading, advection and evaporation. Figure 9 illustrates the approximate spread of the oil released from 5, 0.5 and 0.1 m$^2$ holes at the waterline in a 200,000 dwt Arctic tanker. (The spreading curves assume a crude oil with average spreading properties. They were derived using equations developed by Mackay et al. (1980). The case of a stationary ship is also assumed. If the ship is considered to steam on, the spreading rates would be somewhat greater and would depend on the ship's speed.) Figure 10 shows the corresponding average slick thickness for each of the hole sizes. In the case of the nearly instantaneous release from a large hole, the initial condition is a very thick (40 mm) slick covering an area of some 0.5 km$^2$. After 48 hours, the slick area has increased to some 30 km$^2$, with an average thickness of 1 mm. At this time, 80 to 90% of the area consists of thin sheens 1 to 10 μm thick, and 10 to 20% consists of thick patches 1 to 10 mm thick (Mackay et al., 1980).

The slick(s) will move away from the release point at the speed of the current. After 24 hours exposure on the sea surface, up to 20% of the original oil volume will have evaporated. In the prevailing seas, no significant natural dispersion or emulsification takes place.

**Rough Open Water.** In these conditions, the oil spreading would be approximately the same as in the calm water case; however, the fate of the oil is dominated by the high sea state. Evaporation of the light oil components is enhanced, resulting in a loss of up to 30% of the initial oil volume in 24 hours. The processes of dispersion and emulsification are also important in these rough seas. After 24 hours, 20% of the oil is assumed to disperse naturally. During this period, the oil also forms increasing amounts of stable water-in-oil emulsion, and natural dispersion eventually ceases. The emulsion is extremely viscous and contains 60 to 80% water.

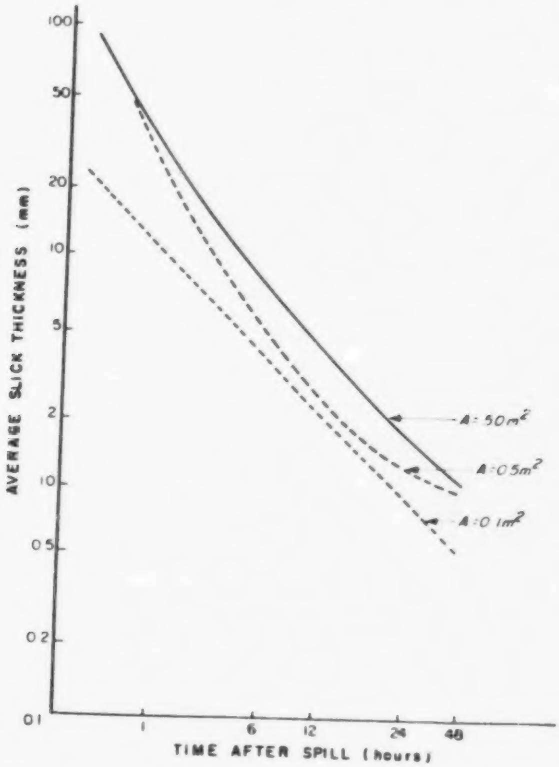


FIGURE 10 AVERAGE SLICK THICKNESS

**Solid Ice Cover.**

**Oil on ice.** Oil spilled onto ice will spread due to gravity forces only (McMinn, 1974). The area the spill covers is dependent on the surface roughness of the ice. The maximum area covered by a 28,000 m$^3$ spill would be 1 km$^2$, with an average thickness of 3 cm. The oil would weather slowly due to the thick slick and cold temperatures. Blowing snow would eventually bury much of the oil.

**Oil in ice.** In this case, all the oil would leak into the ship's track as the tanker continues on at a speed of 10 km/h. The average thickness of the oil along the track is shown in Figure 11. In the case of the 5 m$^2$ hole, all the oil would be contained in the track in thicknesses greater than 1 cm. The oil thickness drops below 1 mm after 24 km in the case of the 0.5 m$^2$ hole and after 56 km in the case of the 0.1 m$^2$ hole.

**Oil under ice.** Oil spilled from the tanker beneath the ice will spread until it reaches its equilibrium thickness. In the absence of ridge keels, rubble fields and multi-year ice features, the oil coverage will range from a minimum of 0.025 m$^3$/m$^2$ (NORCOR, 1975) to a maximum of 0.1 m$^3$/m$^2$. The 28,000 m$^3$ spill with an average coverage of 0.06 m$^3$/m$^2$ results in the oiling of an area 0.5 km$^2$ in size. The oil will be encapsulated by the growing ice within a week and will not weather significantly.

**Moving Ice Floes.** Oil spilled on water amongst moving ice floes will spread as it would in the open water case. Evaporation will be the dominant weathering process and will result in the loss of 30% of the original oil volume after 48 hours. The oil will move away from the release point at a speed of 1 km/h and will be distributed amongst the ice floes. In the absence of waves and high currents, no oil will be carried beneath ice floes; however, oil slicks herded against floes will exceed 1 cm in thickness (Energetex, 1981).

## REVIEW OF CONVENTIONAL LAND-BASED COUNTERMEASURES

The generally accepted strategies for dealing with an oil spill from a tanker utilize various combinations of the following basic procedures:

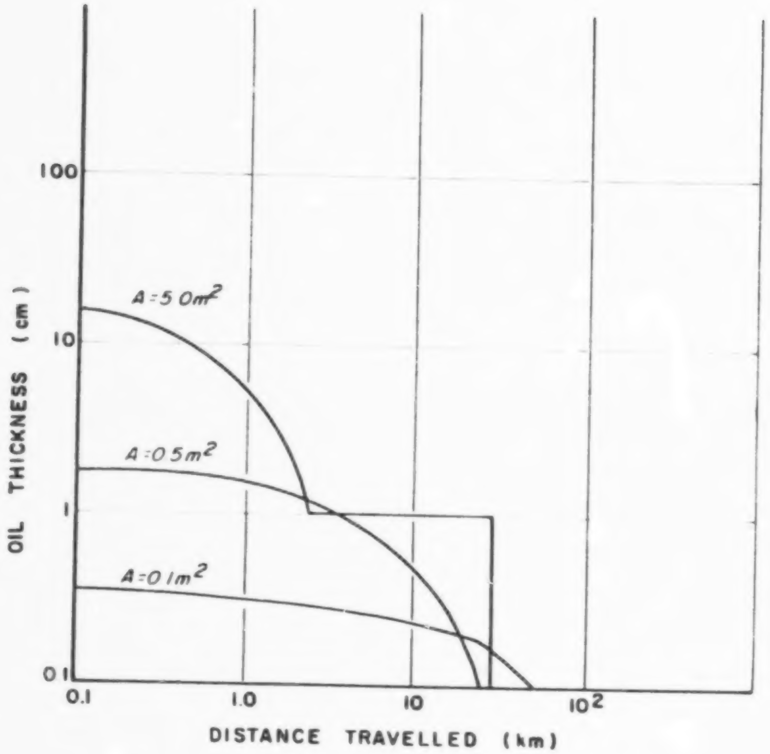


FIGURE 11 OIL THICKNESS IN BROKEN ICE TRACK (spill in ice; tanker continues at 10 km/h; hole at waterline; tank fully vented)

a) stopping the discharge;

b) containment of any released oil either on the open water or after shore contact;

c) mechanical removal of contained oil;

d) combustion of contained oil;

e) chemical dispersion of free-floating oil;

f) disposal of collected oil and oiled debris;

g) monitoring and surveillance of free-floating oil;

h) shoreline cleanup and restoration.

Specialized equipment and techniques have been developed for these operations based primarily on conditions more temperate than those experienced in the Arctic. Several programs have been underway in Canada and elsewhere to modify this equipment to meet the needs of the northern application, or to develop new technologies. A review of the present state-of-the-technology in each of the above control areas was the subject of the first of a series of reports on tanker spill countermeasures in the Arctic (Ross, 1982). The second and third reports dealt with the use of air-deployable igniters for spills in ice (Ross, 1983a) and on-board self-help countermeasures for Arctic tankers (Ross, 1983b).

The report on conventional land-based countermeasures systems provides a very detailed review and analysis of the problem. The following is a summary of its specific and general findings:

### Specific

a) At present, high capacity skimmers are able to handle a maximum of about 150 $m^3$ of oil per hour. For a large tanker spill, recovery devices which could transfer upwards of 1,000 $m^3$/h would be needed for a manageable and efficient operation.

b) For existing dispersants to be effective in the North, they must be applied to the oil spill while it is still fresh, generally less than a day after the oil's release. Large aircraft (DC-6 type) and disperant stockpiles (upwards of 2,500 $m^3$) would have to be permanently dedicated and manned at strategic locations along the tanker route to accomplish this. The considerable cost of doing this is deemed prohibitive.

c) A high percentage of the oil released from a tanker in a complete ice cover setting could be removed by burning during the spring thaw. Upwards of 20,000 air-deployable incendiary devices would be needed to ignite the oil from a large spill. A stockpile of such a large supply of igniters is not currently available.

d) No proven or tested technology exists which can efficiently remove oil from a partial ice cover setting.

e) In a rough, open water situation, little can be done at-source with present equipment to contain or collect oil released from a tanker accident.

### General

The government's technological capability to clean up a major oil spill in the North is not too different from its southern capacity. For both cases, the capability depends strongly on the ocean's surface condition. Open water in the Arctic is often calmer than that in the south due to the North's shorter open water reaches. Containment and collection methods in ice-free situations may therefore be more successful in the North if they can be implemented rapidly. A partial ice cover in northern waters has the potential for mixed effects on an oil removal operation. It may contain the oil sufficiently to allow it to be burned or it may prevent any attempt to artificially contain and mechanically remove the oil. Oil released in a complete ice cover environment is naturally contained and preserved by the ice. The removal of a high percentage of this oil by burning is technically feasible. Under this ice condition, an oil removal operation in the Arctic will be much more effective than one mounted in the open waters of the south.

The above conclusions address the ability of available equipment to remove oil from the northern marine environment assuming that there is no restriction on transporting the equipment and manpower to the site. A northern oil spill cleanup operation, however, has obvious logistical and environmental difficulties which will hamper a countermeasure operation. First, there is a severe lack of local manpower available. Second, land-based transportation is nonexistent; the distances between major southern centres and northern air fields, and between the northern communities and possible spill sites are large. Third, the accommodation and servicing of large work forces in the North will be more difficult than in the southern regions of Canada. Finally, the Arctic climate can be much more severe than in the south. The technological ability to respond to a northern spill may be equivalent to a southern operation but these additional problems necessitate a much more complex support organization and planning structure.

## AIR-DEPLOYABLE IGNITERS

As mentioned previously, one potentially effective technique for dealing with a major oil spill discharged under and into a complete ice cover is to use thousands of igniters to burn the oil when it appears in melt pools on the ice surface during the spring thaw. In order to determine the exact requirements for such an operation resulting from a tanker spill in the Arctic, a study of the numbers of igniters, their production, supply, and deployment was undertaken (Ross, 1983a). The following is a summary of the results.

Two igniters were considered in the study: that developed by Energetex for Dome Petroleum (Energetex, 1982), and that developed by the Defence Research Establishment at Val Cartier (DREV) for Environment Canada (Meikle, 1981).

### Igniter Requirements

A large release of oil from a stationary tanker would require about 40 igniters per hectare of oiled ice for an effective burning operation. For a substantial discharge of oil from a moving tanker, about 15 igniters per hectare would be needed to burn the major oil pools. Therefore, based on the spill scenarios selected for the study, about 2,500 igniters would be needed to burn the oil from a large stationary tanker spill. Up to 30,000 igniters could be needed to ignite the oil from a large release of oil from a moving tanker. Three igniter requirement scenarios were investigated:

No. 1 - 2,500 required in 3 months;
No. 2 - 30,000 required for a stockpile to be ready in 5 years;
No. 3 - 30,000 required in 5 months.

### Igniter Production

The acquisition of the necessary chemicals for the igniter production would likely take 2 to 3 months. Hardware items could have similar supply delays. Unless these raw items were stockpiled at the buyer's expense, production of igniters could only commence 2 to 3 months after an order was placed.

Once the materials were on hand, the limiting steps in the production process would be the mixing and curing stages of the formulation process for solid rocket propellant. The specialized mixtures used in this process are small; therefore, significant time would be needed to produce large quantities of igniters (i.e., 30,000). Since the Dome igniter uses much less of this fuel, it could generally be produced at a higher rate than the DREV unit. Of the ten manufacturers surveyed, a maximum production of 6,000 units (Dome) per month was identified as possible once raw materials were on hand (3,000/month for the DREV). All of the potential manufacturers, except for one, would require that a pre-production run be funded anywhere from 3 to 12 months prior to the first full-scale production order.

The predicted cost of the igniters varied with the manufacturer and with the scenario. The Dome igniter would be generally less expensive to produce. Under the rushed demand of production scenario No. 1, the cost of the Dome igniter ranged from $65 to $67 per unit. The DREV igniter would cost between $72 and $113. For production scenario No. 2, the Dome version would cost between $40 and $65, and the DREV between $54 and $112. A similar cost breakdown for production scenario No. 3 could be expected. Only one potential manufacturer indicated a significant price reduction for higher production situations.

Because of the raw material supply delays and limited production rates, a short-term supply of even 2,500 igniters has found to not be possible. Igniters would therefore have to be stockpiled to handle any major spill which occurs late in the winter (i.e., up to 3 to 4 months prior to breakup). The 30,000 igniters needed for an oil release from a moving tanker could not be made by any one manufacturer even if it occurred very early in the year and 8 months were available to produce the units. The stockpiling of igniters would seem to be the only way to ensure that sufficient igniters are available for cleanup in the spring.

### Igniter Operation

The Arctic settlements in the North considered suitable for land-based operations along the proposed shipping route are Frobisher Bay, Broughton Island, Cape Dyer, Clyde River, Pond Inlet, Nanisivik, Resolute Bay, Rea Point, Johnson Point, Inuvik, Cape Parry, McKinley Bay, and Tuktoyaktuk. The larger of these settlements would serve as intermediate links between the south and the small settlements near the spill site.

While land and sea shipment of igniters would pose no difficulties, both methods are relatively slow and seasonal; land access is available only to the southern Beaufort Sea area. Chartered cargo aircraft would be the only viable shipment mode for the expeditious movement of igniters from the south to northern spill sites.

As examples of the capacities of various transport modes, 30,000 Dome igniters could be moved in 3 transport trucks, 2 train cars, 2 Boeing 737 aircraft, or 5 Douglas DC-3 cargo planes. Because of the heavier weight of the DREV igniter, 3 Boeing 737 and 22 DC-3 shipments would be needed to move 30,000 units.

The igniters would need to be stored in locked, spark-free enclosures, in an absence of other flammable materials. The storage location would also need to be clearly marked as a fireworks storage area.

The major drawback of a land-based helicopter operation would be the transit time to and from the spill site. The available flight time of suitable helicopters limits the time which could be used for the actual igniter deployment. The shipping lanes off Baffin Island are very far offshore; most helicopters do not have the range to fly a sortie to these locations. Depending on the accident location and the size of the spill, from one to more than five helicopters may be needed to deliver the igniters to the spill spite during a spring operation.

Since the igniters would be dropped during the spring melt, the prevailing environmental conditions should not hamper the operation excessively. Sufficient daylight would be available at this time of the year (from 18 to 24 hours) and the probability of good flight conditions is high (70% to 80%).

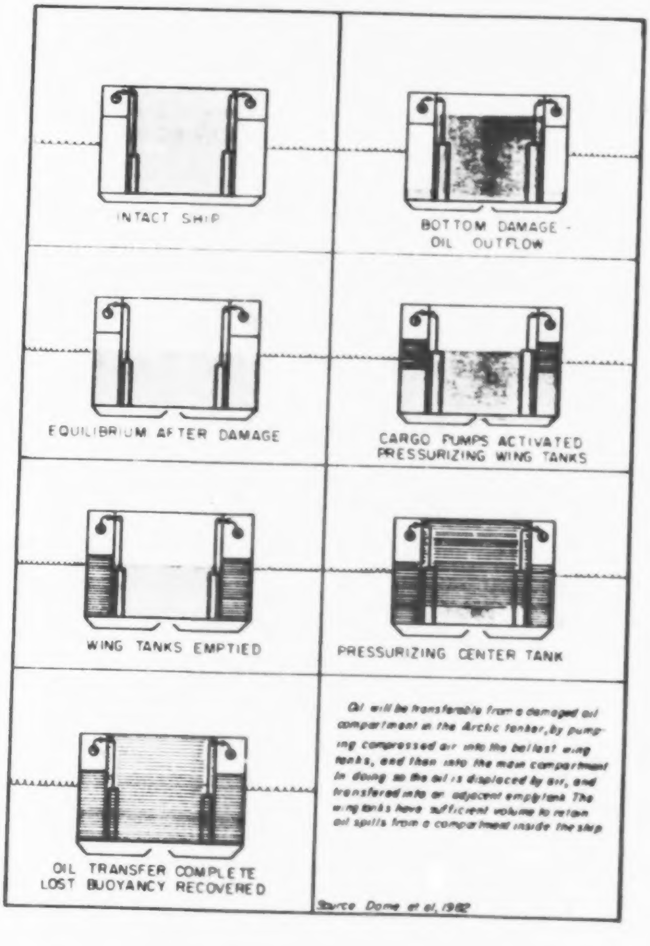
## ON-BOARD SELF-HELP COUNTERMEASURES

The effectiveness of any oil spill countermeasures operation is enhanced by a quick response. This is particularly true for tanker accidents in remote areas. With this in mind, a study was performed (Ross, 1983b) to investigate the feasibility of fighting a tanker spill using various techniques and equipment on board the tanker to greatly reduce or even eliminate the potential impacts of the spill.

Considering the Arctic, the unique design of the tankers proposed for the shipment of Beaufort Basin crude oils to market particularly offers the possibility of equipping the vessel with novel systems for oil spill response. These systems can be placed in two categories: "inboard" countermeasures, to reduce oil losses from cargo tanks in the event of an accident, and "outboard" countermeasures, to deal with oil once it has escaped the confines of the tanker.

### In-Board Countermeasures

**Tank Venting.** Two previous studies (Arctic Offshore Design Ltd., undated; Aaegesen, 1982) have assessed the feasibility and efficiency of reducing oil loss by restricting the flow of air into the ullage space after the tank bottom is ruptured. Based on model studies (Arctic Offshore Design Ltd., undated), Dome Petroleum has proposed a scheme for the tankers to reduce oil outflow (Figure 12).


INTACT SHIP
BOTTOM DAMAGE - OIL OUTFLOW
EQUILIBRIUM AFTER DAMAGE
CARGO PUMPS ACTIVATED PRESSURIZING WING TANKS
WING TANKS EMPTIED
PRESSURIZING CENTER TANK
OIL TRANSFER COMPLETE LOST BUOYANCY RECOVERED

*Oil will be transferable from a damaged oil compartment in the Arctic tanker, by pumping compressed air into the ballast wing tanks, and then into the main compartment. In doing so the oil is displaced by air, and transfered into an adjacent empty tank. The wing tanks have sufficient volume to retain oil spills from a compartment inside the ship*

Source Dome et al, 1982

FIGURE 12 PROPOSED ARCTIC TANKER SPILL CONTROL SYSTEM

The principle by which restricted tank venting operates is as follows. When the damage occurs, the level of oil in the tank begins to drop, thus creating a partial vacuum in the ullage space. If the suction of air into the ullage space is restricted or not permitted, the total pressure head driving the oil outflow is reduced and thus the oil flowrate is reduced. The oil outflow ceases when the pressure difference across the hole is zero.

In the case of bottom damage, Table 3 indicates the reduction in outflow from the tank for the case of a fluid with negligible vapour pressure and an ideal gas in the ullage space. The process is assumed to be isothermal. With the tank vents closed instantaneously, only some 550 $m^3$, or less than 10% of the potential volume, will be released. Based on the Dome model tests, all this oil will be contained by the double bottom. If the vents are not closed instantaneously, more oil will escape. Table 3 also shows the effect of response time on volume of oil lost. Using a minimum delay of 7 min (Aaegesen, 1982), it can be seen that in the case of a 5 $m^2$ hole, the response would be ineffective. In the case of 0.5 $m^2$ hole, only half of the potential spill would be released; for a 0.1 $m^2$ hole, only a small amount would be released.

TABLE 3 EFFECT OF CLOSING TANK VENTS ON OIL LOSS FROM BOTTOM DAMAGE

| Time to Close Vents (min) | | | Oil Lost | |
|---|---|---|---|---|
| 5 $m^2$ hole | 0.5 $m^2$ hole | 0.1 $m^2$ hole | ($m^3$) | (% of potential) |
| 0 | 0 | 0 | 550 | 8.6 |
| 0.4 | 4 | 21 | 1 970 | 30.8 |
| 0.9 | 8.6 | 43 | 3 020 | 47.2 |
| 1.3 | 13.4 | 67 | 3 880 | 60.6 |
| 1.9 | 19 | 93 | 4 660 | 72.8 |
| 2.4 | 24 | 121 | 5 510 | 86.1 |
| 3.1 | 31 | 152 | 6 260 | 97.8 |
| 3.8 | 38 | 190 | 6 400 | 100.0 |

Figure 13 illustrates the effect of restricting tank venting on the outflow of oil from a 0.5 $m^2$ hole in the tank side at the waterline. For the case of the tank partially vented, i.e., kept at a constant partial vacuum by a relief valve (set at 8 x $10^4$ $N/m^2$ or 12 psia in the example), the outlfow is somewhat reduced.

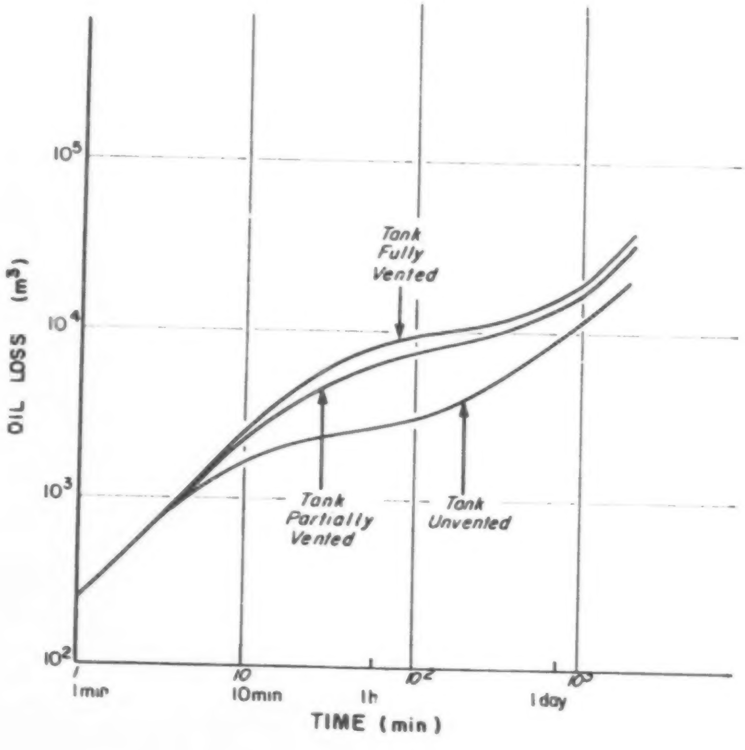


FIGURE 13 EFFECT OF TANK VENTING ON OIL LOSS FROM A 200,000 DWT TANKER WITH A 0.5 $m^2$ HOLE AT THE WATERLINE

The best reduction is achieved by having the vents closed. After 1 hour, 2,200 $m^3$ has been lost as opposed to 8,800 $m^3$ for the unvented tank; in total, 21,000 $m^3$ are lost as opposed to 29,000 $m^3$. Due to the process of water ingestion noted previously, restricted tank venting is not as effective in reducing the total amount of oil lost in the case of a hole in the side as it is for a hole in the bottom.

Figure 14 illustrates the effect of tank venting on the loss of oil through a 0.5 m$^2$ hole in the tank side above the waterline. It can be seen that restricting the tank vents reduces the oil outflow rate, though the total volume lost is the same in all cases. Again, complete instantaneous sealing of the tank vents is the most effective.

In summary, it is seen that restricting the inflow of air into a punctured tank is an effective countermeasure, and that complete instantaneous sealing of the tank vents is the most effective method. In the case of a hole in the tank bottom, this greatly reduces the amount of oil lost; in the case of side damage, it greatly reduces the oil outflow rate; and in the event of holes at or below the waterline, it somewhat reduces the volume of oil lost.

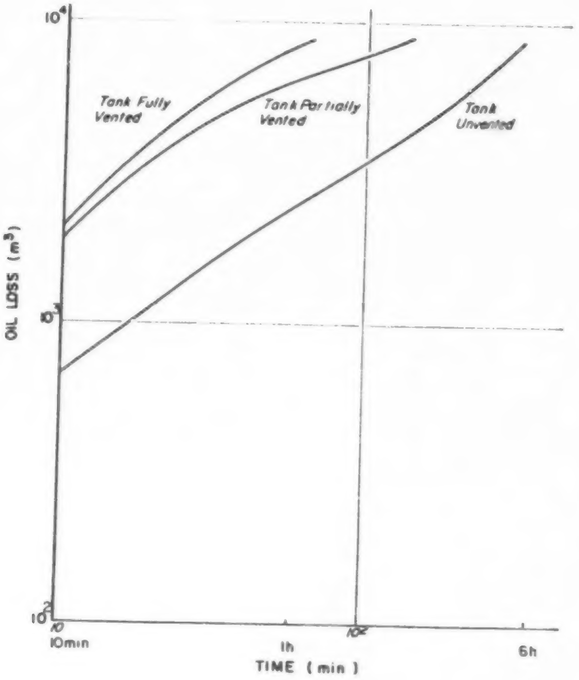


FIGURE 14 EFFECT OF TANK VENTING ON OIL LOSS FROM A 200,000 DWT TANKER WITH A 0.5 m$^2$ HOLE 1 m ABOVE THE WATERLINE

**Emergency Pumping.** Pumps (installed or portable) on board a stricken tanker have two potential uses: pumping oil contained in bottom and wing tanks, and from damaged cargo tanks.

The Arctic tanker has one major advantage over most conventional tankers: a large volume of unused ballast space. The 200,000 dwt version has about 155,000 m$^3$ of storage in the wing and bottom tanks alone. Even fully loaded, the loss of the buoyancy of two adjacent ballast tanks within the double hull would not affect the stability of the tanker (Dome et al., 1982). As such, the Arctic tankers need not wait for the arrival of a lightering vessel before commencing preventive emergency oil pumping.

**Pumping from cargo tanks.** In the event of bottom damage to an Arctic tanker, Dome has devised a system (Figure 12) for recovering the lost oil. This system combines restricted venting of the cargo tank to reduce oil flow out of the confines of the double hull, and the use of compressed air and deepwell cargo pumps to remove the oil to undamaged ballast tanks. This countermeasure will greatly reduce, if not eliminate, the oil lost due to bottom damage. The system, however, will not work in the case of a hole in the side of the ship. In this instance, the water ingested into the tank settles to the tank bottom to a level above the cargo pump suction.

Figure 15 shows the effect on total oil lost of emergency pumping from the cargo tank using a portable pump. In this instance, it is assumed that the hole is at the waterline, the pumping begins instantaneously, and the tank vents are wide open. It can be seen that, although relatively ineffective for the case of a large hole at the waterline, emergency pumping can be very effective in reducing the oil outflow from a tank with smaller holes.

Figure 16 shows the effect of response time on the effectiveness of pumping. Response time is not a factor in the case of a large hole, since pumping alone is not a very effective control technique. It is interesting to note that response delays of up to an hour have only a minor effect on the efficiency of pumping for smaller holes. The price of delaying 1 hour in commencing pumping at 1,000 $m^3/h$ is a decrease in the reduction of total oil outflow from 21,000 to 20,000 $m^3$ for a 0.1 $m^2$ hole and 12,000 to 11,000 $m^3$ for a 0.5 $m^2$ hole.

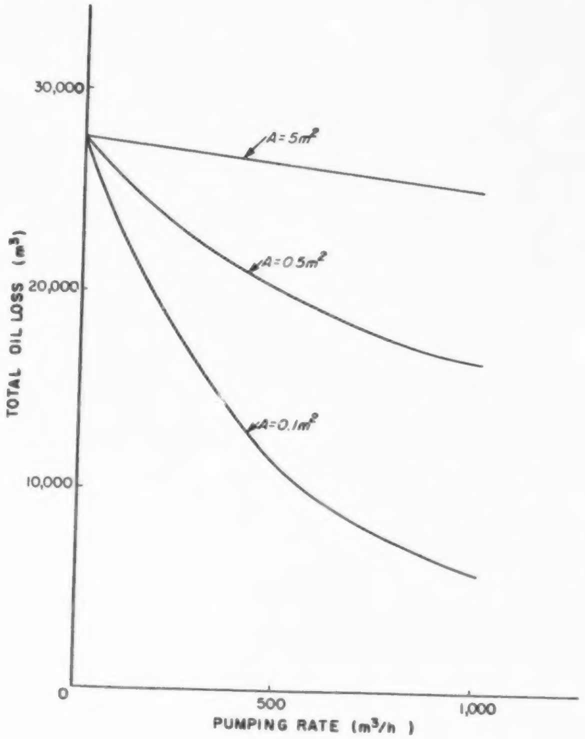


FIGURE 15 EFFECT OF EMERGENCY PUMPING (tank fully vented, hole at waterline)

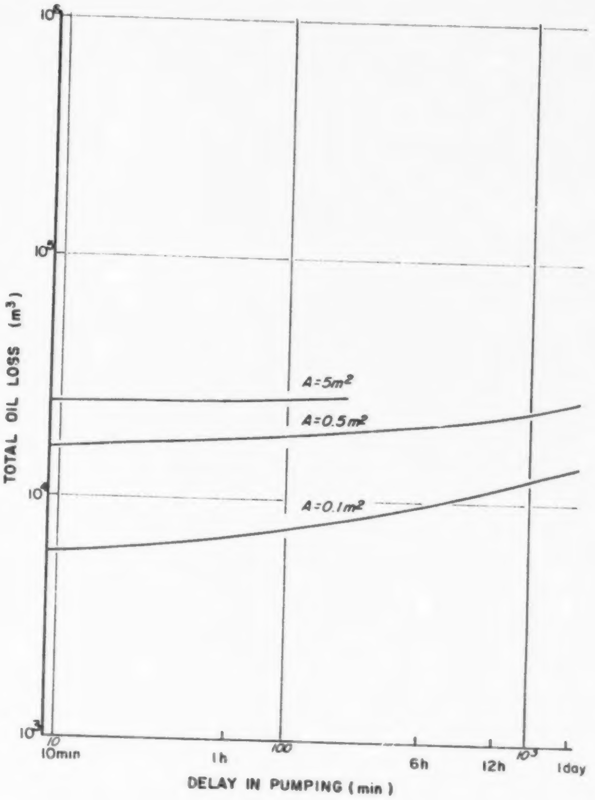


FIGURE 16 EFFECT OF RESPONSE TIME ON EFFECTIVENESS OF EMERGENCY PUMPING (200,000 dwt tanker, hole at waterline, tank fully vented, pumping, at 1,000 $m^3/h$)

**Pumping from wing tanks.** In the event of a hole above or below the waterline, oil will be contained within the wing tanks of the vessel (Figure 2). In the case of a hole above the waterline, the vessel's ballast pumps may be able to recover this oil; however, this will not be the case for a hole beneath the waterline. In this instance, the oil will be floating on water inside the wing tank. The use of a portable pump will be required to remove this oil to a safe compartment. In addition, the use of a portable pump in this oil containment area will reduce the outflow of oil from holes less than 10 m below the waterline (Figures 2 and 8), as illustrated in Figure 17. The combination of the containment capacity of the wing tank plus pumping oil at 1,000 $m^3/h$ from inside the wing tank results in considerable reductions in the volume of oil spilled. As before, the efficiency of pumping is greater for small holes than for larger ones.

**Dump Valve.** Although pumping is an extremely effective countermeasure for small holes, it is limited for larger holes. In addition, the time required to deploy portable pumps in the affected tank(s) reduces the effectiveness. In order to significantly reduce the loss of oil, a system is required to quickly transfer large amounts of oil from the affected tank.

One proposed concept that meets the above criterion is a semi-automatic dump valve in the cargo tank. This approach, depicted in Figure 18, consists of a large diameter pipe installed on the centreline bulkhead of each tank. The pipe, in this case 1 m diameter, leads from the cargo tank to the bottom ballast tank on the opposite side of the vessel.

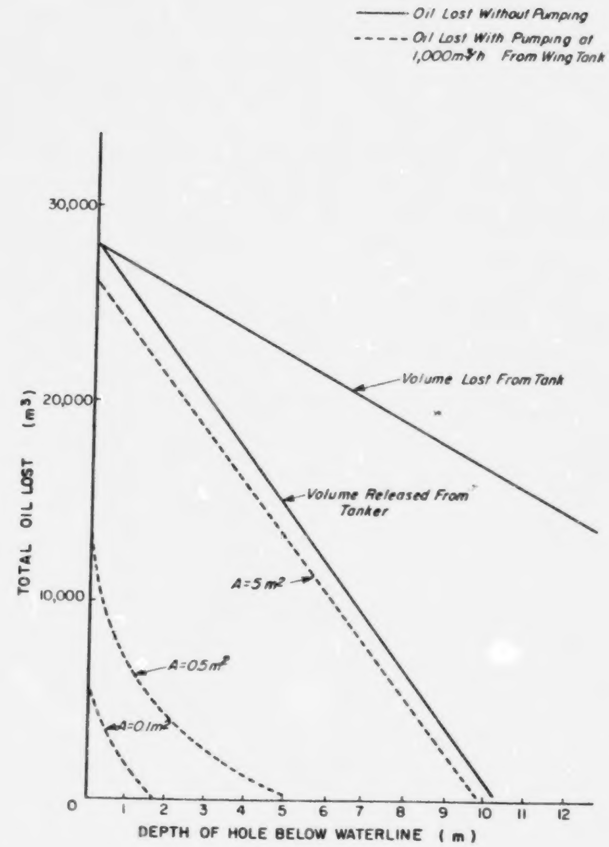


FIGURE 17 EFFICIENCY OF PUMPING FROM WING TANK (200,000 dwt tanker, tank fully vented)

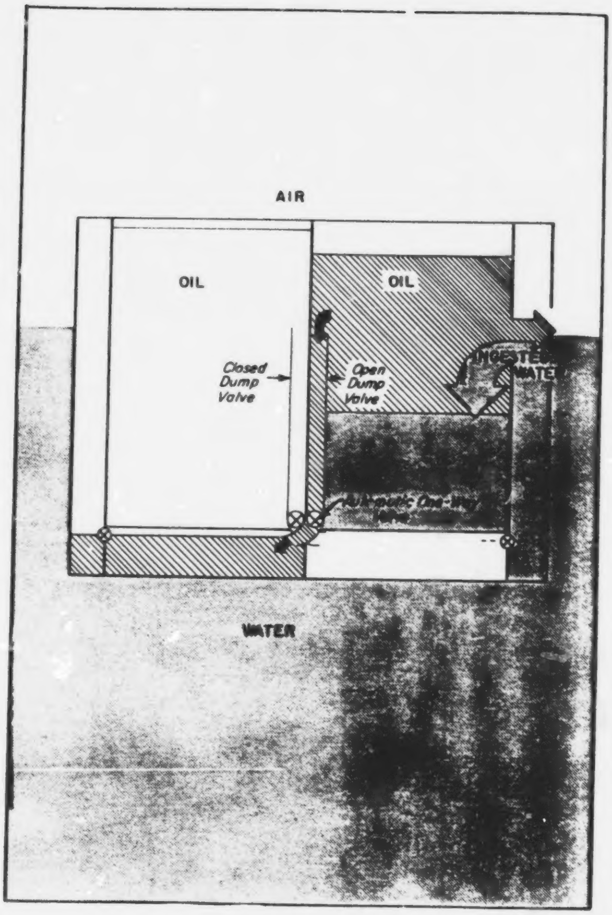


FIGURE 18 DUMP VALVE OPERATION

The pipe is fitted with an automatic one-way valve which is closed in normal operations. The top of the pipe is located at the waterline to prevent it from being overtopped by water ingested into the tank. In the event of damage, the valve opens and oil begins to pour through the pipe from the tank to the undamaged ballast space. The efficiency of such a system in reducing oil losses from a hole at the waterline is shown in Figure 19. Even for large holes, the volume of oil prevented from entering the sea is considerable.

The use of a dump valve in the case of bottom damage would also be effective. If the tank vents are not sealed, the dump pipe will remove a portion of the oil that would normally be released. If the tank vents are shut, the dump valve will permit hydrostatic equilibrium to be reached sooner and continue to remove oil, building up a water cushion beneath the oil remaining in the affected tank.

**Gelling and Solidifying Agents.** The injection of gelling and solidifying agents into a damaged cargo tank is not an effective on-board self-help countermeasure (with the possible exception of the use of fast-acting chemicals to produce a plug) because of the large volumes of chemicals and lengthy mixing times required.

**Dispersants.** The injection of dispersants into a damaged cargo tank is not an effective on-board self-help countermeasure. The time required for mixing the dispersant and oil in relation to the oil loss rate is inadequate, and the large volume of dispersant required is prohibitive.

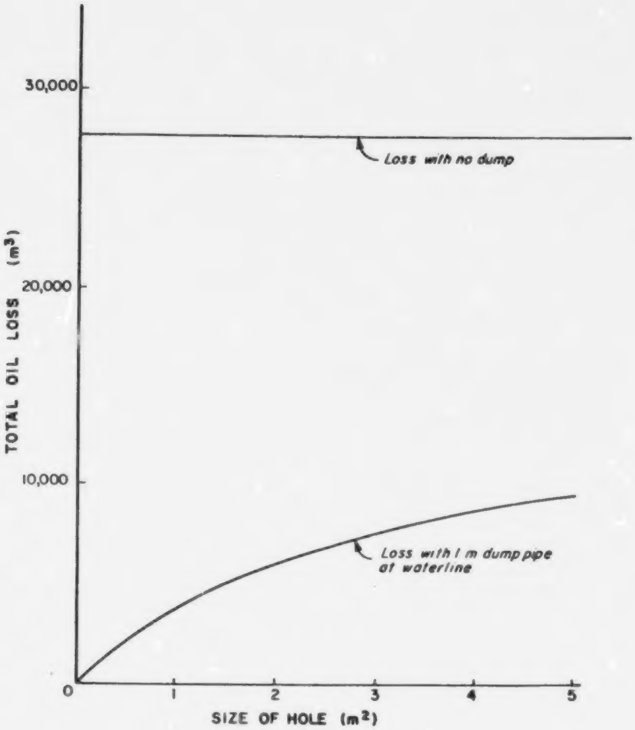


FIGURE 19 EFFECT OF DUMP VALVE (200,000 dwt tanker, tank fully vented, hole at waterline)

**Tank Liners or Bladders.** The installation of liners or bladders could significantly reduce oil outflow from a cargo tank but their applicability is dependent on tank design and washing procedures.

**Plugs and Patches.** Unless qualified divers with appropriate support facilities are to be stationed on an Arctic tanker, the use of plugs and patches to reduce oil loss from damaged cargo tanks is not considered an effective on-board self-help countermeasure.

**In Situ Burning.** Burning oil in cargo tanks is not an effective on-board self-help countermeasure for safety reasons and because of the low oil combustion rate in relation to the oil outflow.

**Out-board Countermeasures**

**In Situ burning.** The use of in situ burning to dispose of oil spilled on, in, or under Arctic sea ice is a well-proven technique (NORCOR, 1975; Dickins and Buist, 1981); in situ burning of oil slicks even on open water conditions shows good potential as an on-board self-help countermeasure.

**Burning in ice.** Field-proven, air-droppable oil slick igniters suitable for use on Arctic oil spills in ice conditions are commercially available (Meikle, 1981; Energetex, 1982). A report on igniter requirements for Arctic tanker oil spills in ice (Ross, 1983a) has concluded that about 15 igniters per hectare would be required for areas with an oil coverage in the range of 0.001 $m^3/m^2$; 25 igniters per hectare would be required for areas with an oil coverage in the range of 0.01 $m^3/m^2$; and 40 igniters per hectare would be required for areas with an oil coverage in the range of 0.1 $m^3/m^2$. The latter value is considered to be a maximum.

If the tanker were to have an accident in solid ice, remain at the site and spill all its oil onto the ice, some 2,500 igniters would be required. In excess of 90% of the oil could theoretically be burned. If all the oil spills under the ice, no igniters would be required immediately as the oil would not be available for burning until the ice begins to melt in the spring.

If the tanker continues to steam ahead at a rate of 10 km/h, the oil will be contained in the broken ice track of the vessel. Figure 11 shows the average oil thickness in the 68 m wide track as a function of distance from the accident location and hole size. For the purpose of calculating igniter requirements for this situation, it is assumed that oil thicknesses less than 1 mm would not be immediately ignited. Table 4 shows the igniter requirements to deal with the various hole sizes, as well as the percentage of the volume of spilled oil that lies within the area to be burned. It can be seen that about 5,000 igniters would provide the capability to ignite the oil existing in burnable thicknesses. The igniters could be dropped from a small helicopter (Bell 206B) in about 25 sorties or by a medium helicopter (Bell 212) in about 8 sorties (Ross, 1981b). The total time required to accomplish such an operation would depend on flying conditions, daylight, distance from the tanker to the oiled area, and oil pool size and separation. At an average igniter drop rate of 3/min, the actual deployment would require some 28 hours.

TABLE 4 IGNITER REQUIREMENTS FOR A TANKER SPILL IN BROKEN ICE TRACK

| | Length of Oiled Track (km) | | | | |
|---|---|---|---|---|---|
| Hole Size ($m^2$) | 0.1 $m^3/m^2$ coverage | 0.01 $m^3/m^2$ coverage | 0.001 $m^3/m^2$ coverage | Burnable Thickness (% of total) | Approximate Number of Igniters |
| 5 | 1 | 29 | 0 | 100 | 5,000 |
| 0.5 | 0 | 12 | 18 | 100 | 4,000 |
| 0.1 | 0 | 0 | 60 | 30 | 6,000 |

It is interesting to note that the number of igniters required almost doubles if the tanker continues on after the accident; the logistics of the igniter deployment operation become more complex. For the most efficient response to an oil spill on or in a complete ice cover, the tanker should remain stationary until the oil outflow ceases. Obviously, burning operations should not commence until the vessel has moved a safe distance from the spilled oil.

**Open water burning.** Even in the case of a spill on open water, in situ burning may be an alternative, though this is not yet a proven concept. There have been cases of tanker accidents where the oil accidentally caught fire and most of the spilled oil was consumed (e.g., Goodier and Siclari, 1981; Horn and Neal, 1981). The combustion process does not seem to be severely affected by regular waves such as a swell, although choppy seas may extinguish the fire (McAllister and Buist, 1981).

The key to successful open water in situ combustion is to contain the oil at thicknesses much greater than 1 mm during the burning. An immediate response from the tanker increases the chances for effective open water burning since the slick is thick and the oil fresh; thus, potential combustion efficiency and flame spreading are enhanced.

One approach to containing the oil is to deploy a fireproof barrier around the slick. Although fireproof booms are available (e.g., Buist et al., 1983; Meikle, 1983), the same difficulties in deployment would be faced as noted for conventional containment booms. As such, the use of fireproof booms as an on-board self-help countermeasure is not recommended.

The second approach is simply to set the free-floating slick(s) on fire. This technique has been tried on past tanker spills, with varying success. For small slicks of weathered crude oil or bunker, the oil is difficult to ignite. Also, the combustion is not efficient and leaves behind large volumes of heavy, viscous residue that are difficult to deal with (Thompson et al., 1979). However, in cases where large, thick, slicks of fresh crude oil or light distilled product have ignited, the combustion is intense and much of the oil burns (Horn and Neal, 1981). This would be the case for a burning operation initiated from a holed Arctic tanker shortly after an accident.

**Containment and Recovery.** Containment and recovery operations (except for small spills in sheltered waters) are not considered effective on-board self-help countermeasures because of the difficulty in deploying equipment from the tanker and the length of time required to recover the oil using best available skimmer technology.

**Dispersants.** The use of dispersants, except for small slicks on open water in the presence of waves, is not an effective on-board self-help countermeasure. Only limited amounts of oil can be treated in the time available prior to increases in oil viscosity beyond the point below which dispersants could be effective.

**Gelling and Solidifying Agents.** The use of gelling or solidifying agents on slicks is not considered an effective on-board self-help countermeasure because of the large volumes of chemicals required and the difficulties in applying them.

### Recommended Equipment Packages

**In-board Countermeasures.** The following systems should be considered for installation on proposed Arctic tankers to reduce oil outflow in the event of an accident:

a) Restricted Tank Venting

- automatic system to seal all tank vents in the event of damage;
- vacuum relief valves on all tank deck vents with set point below equilibrium ullage pressure for holed tanks with sealed vents;
- tank structure capable of withstanding partial vacuum;
- pressure sensor system to control inert gas topping up system.

b) Dump Valve

- large diameter pipe mounted on centreline bulkhead of each cargo tank leading to bottom ballast tank(s);
- semi-automatic valve controlled from bridge to be opened in the event of tank damage.

c) Emergency Pumps

- self-powered portable pumps capable of being inserted into cargo and wing-ballast tanks;
- 1,000 $m^3$/h capacity with hose and booster pump capable of discharging oil into any other tank on vessel or to another vessel;
- special airlock to permit insertion of pump into cargo tank under partial vacuum;
- portable, self-powered inert gas generator;
- oil monitoring system for wing-ballast tanks.

The potential spill reduction of such a system is illustrated in Figure 20.

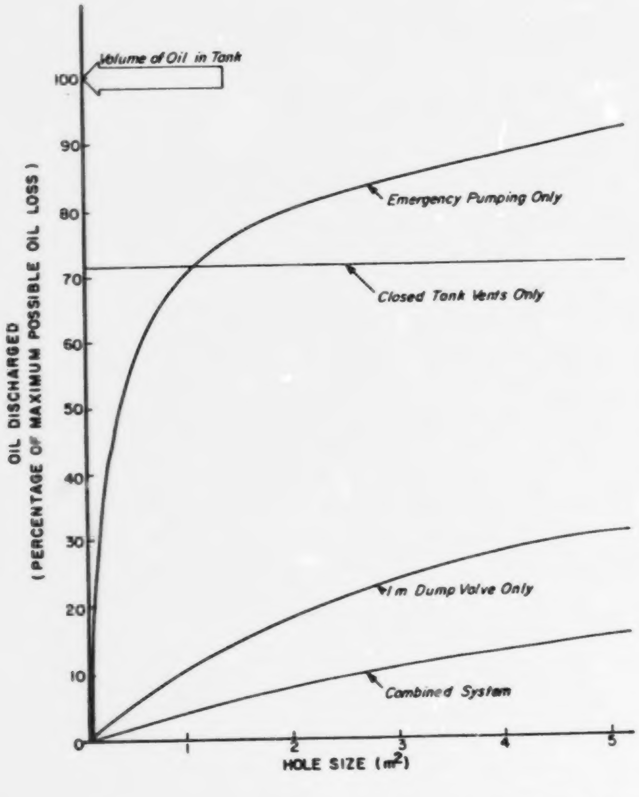


FIGURE 20 COMBINED EFFECTIVENESS OF IN-BOARD COUNTERMEASURES (200,000 dwt tanker, restricted tank venting, 1 m diameter dump valve, 1,000 $m^3$/h emergency pumping, hole at waterline)

**Out-board Countermeasures.** The following equipment should be considered for placement on proposed Arctic tankers to respond to oil spills in a complete ice cover:

a) at least 5,000 air-droppable oil slick igniters and a helicopter; and

b) at least four satellite-tracked/radio direction finder buoys.

Consideration should be given to carrying the following equipment on-board Arctic tankers to respond to small oil spills:

a) Containment and Recovery

- small, 40 HP workboat;
- lightweight containment boom (1.5 shiplengths);
- small skimmer;
- pump and hose;
- small storage bladders;
- sorbents.

b) Dispersants

- 10 m$^3$ dispersant concentrate;
- either a helicopter spray bucket or vessel spray gear.

## CONCLUSIONS

The application of conventional land-based oil spill countermeasures would be limited in dealing with oil released from a tanker accident in Canada's Arctic waters. Only in situ burning of oil spilled in complete ice cover conditions has the potential to efficiently remove significant amounts of oil. Twenty-five hundred air-deployable igniters would be required in the spring following an accident where the ship remained stationary during the oil release. Thirty thousand could be needed if the ship captain chose to steam ahead during the oil discharge.

It is unlikely that these igniters could be produced on a "demand" basis without a significant level of pre-production funding for the manufacturers. At best, between 3,000 and 6,000 igniters could be produced per month. The delivery of the igniters to strategic locations along the proposed tanker route could be accomplished by cargo aircraft. The deployment of the igniters at the spill site during spring thaw should be feasible but could be hindered by excessive helicopter transit times to and from the spill site.

The design of the proposed Arctic tankers offers the possibility of equipping the vessel with special systems for oil spill response. These systems can be placed in two categories: "in-board" countermeasures to reduce oil losses from cargo tanks in the event of an accident, and "out-board" countermeasures to deal with oil on water or ice.

The in-board countermeasures found to be potentially effective and worthy of further consideration are restricted tank venting, a special dump valve, and portable emergency pumps. The restricted tank venting operates by sealing all air vents of the damaged cargo tank, thereby allowing a partial vacuum to build up in the tank as oil leaks out. This slows and eventually stops the outflow of oil. A special dump valve mounted in each cargo tank could be opened in the event of damage to drain the tank contents to a safe compartment elsewhere in the tanker. Emergency pump systems could be used to reduce oil outflow from small leaks and would be necessary to recover oil floating in damaged cargo and wing tanks. The general system specifications and applicability of these in-board countermeasures are summarized in Table 1. The combination of these three in-board countermeasures has the potential to reduce the volume of oil lost from a breached cargo tank by 85 to 99% for the damage situations investigated.

Only one out-board countermeasure was found to be potentially effective for large spills, namely burning of crude oil spilled on or amongst ice. By carrying 5,000 igniters and a helicopter aboard the tanker, much of the spilled oil could be ignited and burned. Burning of crude oil on water could also be an effective on-board self-help countermeasure since the oil would be fresh and in thick slicks. Further research is required to evaluate this potential open water countermeasure.

In order to be able to have a capability to deal with small spills from the vessel, consideration should be given to placing on board the tanker a package of booms, a skimmer, a small workboat, pumps, small storage bladders, a small amount of dispersant, and helicopter- or vessel-mounted dispersant application equipment.

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# AN OVERVIEW OF POTENTIAL LARGE OIL SPILLS OFFSHORE CANADA AND POSSIBLE RESPONSE STRATEGIES

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## INTRODUCTION

This paper is based on a detailed study written in early 1982 (Ross, 1982). The objective of the study was to prepare a critique on worst-case oil spills that could occur in various regions of the Canadian marine environment over the next decade, and to outline and evaluate strategies and technologies for dealing with these spills, based on existing knowledge and capabilities. An article covering some aspects of the original report has already appeared (Thornton and Hume, 1982). This paper discusses several factors not dealt with in the newsletter article and provides an update on the original study.

## SOURCES AND TYPES OF MASSIVE OFFSHORE OIL SPILLS

Current and proposed offshore petroleum-related activities pose a threat of major oil spills to Canada. One activity is the shipment of oil by very large tankers through coastal waters. Another is the exploitation of undersea oil through drilling, production, and transportation operations. Figure 1 shows the locations of all offshore oil activities in Canada, either ongoing or in the planning stage.

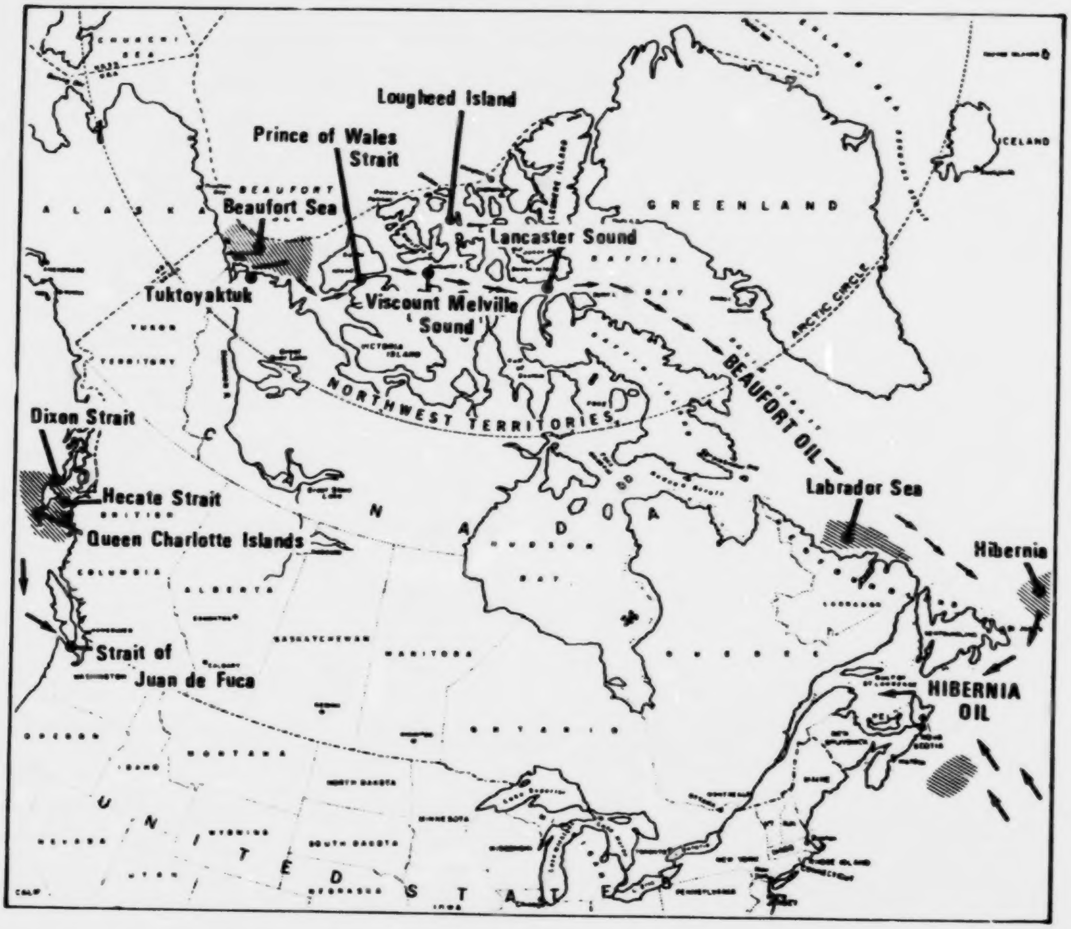
Lougheed Island
Prince of Wales Strait
Beaufort Sea
BEAUFORT
ALASKA
GREENLAND
ICELAND
Lancaster Sound
BAFFIN BAY
Tuktoyaktuk
Viscount Melville Sound
VICTORIA ISLAND
ARCTIC CIRCLE
BEAUFORT OIL
NORTHWEST TERRITORIES
Dixon Strait
Hecate Strait
Queen Charlotte Islands
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
CANADA
HUDSON BAY
Labrador Sea
Hibernia
HIBERNIA OIL
Strait of Juan de Fuca
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
MINNESOTA
UNITED STATES
NEW YORK

FIGURE 1 LOCATION OF OFFSHORE PETROLEUM AREAS IN CANADA

Although large offshore oil spills associated with these activities can differ widely, all fall into only two major categories regarding spill countermeasures at the source. The first is an immediate batch spill which involves the release of a large amount of oil over a relatively short period of time. The primary sources for this kind of spill include the very large oil storage facilities that will become part of the proposed offshore production facilities, the very large tankers being considered to ship offshore oil to Canadian or foreign markets, and, of course, the large crude carriers that already ply coastal waters in southern Canada. The other spill type is a continuous discharge of oil over a long period of time, such as oil-well blowouts. These could occur in any of the offshore regions of Canada (shown in the shaded areas of Figure 1) where offshore wells are being, or could be, drilled or produced.

The strategies adopted to clean up marine oil spills, whether batch spills or blowouts, are clearly a function of the location of the accident and the environmental conditions prevailing during the time of the spill. In order to develop an overall strategic position to deal with the problem, it becomes necessary to analyze the various specific offshore areas in Canada where massive spills could occur.

When the offshore areas and activities shown in Figure 1 are analyzed in depth (Ross, 1982), it becomes clear that only a few crucial and obvious variables determine the general behaviour and cleanup potential of all major offshore spills. These are:

a) spill mode: blowout or batch spill;

b) discharge period: hours, days or months;

c) sea state: low or high;

d) ice conditions: stationary ice cover, partial ice cover, or ice-free; and

e) water depth (for blowouts only): shallow or deep.

When each offshore activity is reviewed with respect to the above variables, a list of spill possibilities results. For example, when the Hibernia oil development on the Grand Banks is analyzed, eight spill situations are generated:

a) Batch spill (e.g., tanker) at Hibernia: no ice; discharge time in hours or days; low or high sea states.

b) Nearshore tanker spill: no ice; discharge time in days; low sea state.

c) Nearshore tanker spill: no ice; discharge time in days; high sea state.

d) Nearshore tanker spill: no ice; discharge time in hours; low or high sea states.

e) Above-sea blowout (platform remains on station): no ice or some ice; low or high sea states.

f) Subsea blowout: no ice; low sea state; water depth 80 m.

g) Subsea blowout: no ice, high sea state; water depth 80 m.

h) Subsea blowout: partial ice; water depth 80 m.

When similar lists are developed for each specific offshore area/activity and are then combined, the total number of spill possibilities becomes extensive. Many of these, however, are very much alike and can be grouped together. When this is done, it is found that 12 general spill situations can be used to encompass all possible offshore spill situations in Canada. These are shown in Table 1.

## EVALUATION OF CONTROL STRATEGIES

A three-phase analysis was performed to identify appropriate countermeasures strategies for dealing with the 12 representative oil spills summarized in Table 1 (Ross, 1982). First, a critique on the general behaviour of offshore oil spills was made; second, an analysis of the countermeasures state-of-the-art was performed (see Thornton and Hume (1982) for a summary of this analysis of countermeasures techniques and equipment); third, and most important, a detailed examination of each of the 12 specific spills was carried out. This latter analysis focused on the likely behaviour and fate of each spill and various countermeasures techniques (and their likely success) in dealing with the spill. Although it is not appropriate here to present detailed information on these specific spill behaviour and control scenarios, the following summary discussion may be sufficient to indicate the major and general problems associated with fighting offshore oil spills in Canada.

Some of the spill situations listed in Table 1 are relatively straightforward to deal with, and others would appear to be very difficult. The representative scenario in the table are ranked roughly in terms of "countermeasures difficulty", or "ineffectiveness of human intervention", or "percentage of spilled oil left on surface to threaten resources". The oil spills at the top of the list are evaluated to be relatively easy to counteract, the effectiveness of the control operation is considered to be high, and the oil that is left on the water surface is low after human and environmental forces have had their effect. Correspondingly, the spills at the bottom of the list are almost impossible to control due to

TABLE 1 REPRESENTATIVE MAJOR OFFSHORE OIL SPILLS

| Case No. | Source of Spill | Discharge Period | Ice Conditions | Sea State | Water Depth | Representative Scenario | Other Examples |
|---|---|---|---|---|---|---|---|
| 1 | Surface Blowout | Months | Ice or No Ice | Low or High | N/A | Artificial Island; S. Beaufort Sea | Batch spill within APLA |
| 2 | Subsea Blowout | Months | Stationary Ice Cover | N/A | 200 m | High Arctic | |
| 3 | Subsea Blowout | Months | No Ice | Low or High | 200 m | Dixon Entrance | Eastern Arctic, Labrador Sea (summer) |
| 4 | Tanker | Hours or Days | Ice Cover | N/A | N/A | Viscount Melville Sound | Northwest Passage (winter) |
| 5 | Subsea Blowout | Months | No Ice | Low | 20-80 m | S. Beaufort Sea; summer | Grand Banks, at time |
| 6 | Subsea Blowout | Months | Moving Ice Cover | N/A | 20-80 m | S. Beaufort Sea; winter | |
| 7 | Tanker | Days | No Ice | Low | N/A | S. Beaufort Sea; summer | East and west coasts, Northwest Passage, at times |
| 8 | Subsea Blowout | Months | No Ice | High | 20-80 m | Grand Banks | S. Beaufort Sea, at times |
| 9 | Subsea Blowout | Months | Partial Ice | N/A | Any | Lancaster Sound/ Baffin Bay | S. Beaufort Sea, Eastern Arctic; Labrador Sea |
| 10 | Tanker | Days | No Ice | High | N/A | Newfoundland Coast | All tanker routes |
| 11 | Tanker | Hours | No Ice | Low or High | N/A | Nova Scotia Coast | All tanker routes |
| 12 | Tanker | Hours or Days | Partial Ice | N/A | N/A | Baffin Bay | S. Beaufort Sea, Northwest Passage, East Coast (winter) |

technological or logistical factors, and much of the spilled oil is ultimately left on the water surface to threaten onshore or nearshore resources and activities.

### Blowouts vs Tanker Spills

It is clear that blowouts are much more amenable to control than are tanker spills. Of the seven blowouts and five tanker spills analyzed, all blowouts but two were listed in the upper half of Table 1; all tanker spills but one were listed in the bottom half. The only two blowouts that were considered to be particularly troublesome were a thinly spread one in a partial ice environment (Case No. 9), and a shallow-water one in which a water-in-oil emulsion was considered to form and which was assumed to occur during rough ocean conditions (Case No. 8). All others are believed to be highly controllable. The primary reasons for this are that the oil slick formed as a result of a blowout is generally thin and fresh, and hence dispersable; the slick is generally contained within a reasonable surface area above the blowout source; and the amount of oil discharged per unit time is modest when compared to a typical tanker spill.

### Ice Cover vs Partial Ice

Oil spill control specialists working in the Arctic have often made the point that the ice generally is an asset rather than a hindrance when dealing with spills. The results of this study support that contention, insofar as a complete ice cover is concerned. Although tanker spills generally are very difficult to deal with, one taking place in a complete ice cover environment (e.g., Scenario No. 4) can be considered to be fairly controllable. The reason is that the oil is contained and kept thick and fresh by the ice for many months, during which time a sophisticated igniter deployment program can be planned to burn the oil in the spring as it emerges on the ice surface. A similar, but more difficult, situation occurs for a shallow-water oil blowout under a moving ice cover (Case No. 6). For a deep-water oil blowout under moving ice (Case No. 9), the ice similarly encapsulates and contains the discharging and uprising oil; unfortunately, however, the oil's concentration is not sufficient for combustion.

Aside from its inhibiting effect on the spread and aging of spilt oil, ice can also benefit the countermeasures process by acting as a platform for the operation (as described in Case Nos. 1 and 2), where the ice is relatively stationary and safe to operate from. In addition, landfast ice tends to protect sensitive shorelines during periods of freeze-up and breakup when offshore oil spill countermeasures become very difficult.

It is during these partial-ice offshore conditions that ice is certainly not "nice" but rather is a great hindrance and even a hazard to an oil spill control operation. The presence of moving ice floes in the vicinity of an oil spill not only prevents the application of conventional booms and skimmers in a countermeasures operation, but also permits the rapid spread of oil on the continuous surface of water. This spreading action does not favour in situ burning techniques. Worse yet, the ice tends to damp water turbulence and hence reduces the rate of natural dispersion of the oil into the water and the potential effectiveness of chemical dispersants.

In summary, there are as yet no existing countermeasures technologies or concepts that are capable of dealing with the problem of an oil spill in a partial ice situation.

### Sea State

As in a partial ice environment, oil spill control measures involving mechanical containment and recovery equipment are not applicable in a rough sea environment. Booms and skimmers fail when sustained winds greater than about 20-25 kt and sea states greater than 3 or 4 are in effect. In fact, no countermeasures techniques are appropriate during very bad weather conditions. A number of scenarios involving high sea state demonstrate, however, that a dispersant operation can be effective in fairly rough ocean conditions which are considered to be too severe for a successful booming and skimming operation. The reason for this is that a dispersant operation (either ship- or aircraft-based) is less sensitive or vulnerable to winds and waves than is a mechanical booming operation. In booming, the surface oil is elusive and prone to resist containment through entrainment and natural dispersion processes caused by high currents or waves. Dispersant techniques are far easier; the chemical simply needs to be applied to the oil as uniformly as possible, and the mixing of the ocean is enough to do the job, especially in turbulent seas and with the use of concentrate dispersants. Thus, in general, rough or moderately rough ocean conditions tend to limit the applicability of a physical control and recovery operation, but tend to enhance the opportunities for having an oil spill disperse into the water naturally or with the assistance of chemical agents. Of course, in very bad weather (in gales and storms), no countermeasures operation should be attempted, if for safety reasons alone. In any account, it is during these rough periods that oil spills tend to be broken up naturally and dispersed into the water.

### Response Time Limitations

The limitations of existing technologies to operate effectively in rough ocean conditions, however, are not the main problem in dealing with large tanker spills. In reviewing the various tanker scenarios not involving ice, one quickly realizes that the limiting factor is not technology but rather a lack of time to do something useful before the spill spreads or weathers beyond control. For example, if existing offshore booms, skimmers, pumps and storage units were available immediately at the site and time of a tanker spill in reasonably calm weather conditions, the spill could be collected relatively easily. If sufficient amounts of dispersant and appropriate delivery systems were similarly available, the oil could be effectively treated. Operations involving either of these control techniques, however, can only be mounted after several hours or even days of assembling manpower, equipment and material, and delivering these to the accident site. By this time, the oil is too widespread and viscous. All open-water scenarios involving tanker spills (e.g., Case Nos. 7, 10, 11) suffer from this problem of insufficient time. Only in cases where several days of advance warning of an impending spill are available (e.g., Case No. 10) can something be done. This situation, however, is very improbable.

It is difficult to imagine many countermeasures strategies or approaches for dealing satisfactorily with this "time" problem. One could propose stockpiling thousands of drums of dispersant and large dedicated aircraft at strategic locations across the country; or that all tankers have sufficient equipment, materials and trained personnel on board at all times; or that all crude oil cargoes be chemically altered to congeal or disperse on entering water; etc. Although such ideas may seem fanciful, impractical or economically unfeasible, the creative approach is all that remains after having to rule out conventional methodologies. Without innovative thinking and R & D, one is only left with the hope that the next major tanker spill in Canada will involve a rather lengthy discharge period (e.g., Scenario No. 7), that the oil escaping the primary control effort at source will be swept away from and not towards coastal regions, and that, for oil that does threaten or impact shorelines, an expeditious and well-planned shoreline protection and cleanup program be implemented.

### Offshore Booms and Skimmers

Indications are clear that there are very few useful applications of offshore booms and skimmers to potential offshore major oil spills in Canada. The only truly practical use of such technology in the dozen representative spills studied is for a shallow-water blowout in moderately calm, ice-free waters. The only Canadian scenario or environment where this applies is the southern Beaufort Sea in summer. However, the above-noted conditions are also ideal for using a fireproof boom in a combustion operation. Offshore booms and skimmers, then, would simply be a back-up to the in situ burning operation. In all other scenarios, offshore booms and skimmers have either no role whatsoever or only a limited, questionable role. In rough environments, such as the Labrador Sea, the Newfoundland Grand Banks or the west coast (e.g., Dixon Entrance), booms and skimmers could be used on oil blowouts during rare periods of calm-to-moderate weather. Overall, however, they would not likely make a significant difference in the ultimate environmental impact of the spill. For the calmer environment of Lancaster Sound and Baffin Bay during the short open-water season, booms and skimmers could be utilized; however, the oil slicks generated by deep-water blowouts in this Arctic area would probably be too thin and widespread to be physically contained, concentrated and collected efficiently. For tanker spills, as already discussed, offshore booms and skimmers, however effective they are, have a very limited application because of the problems of reaching the accident site before the spill spreads to unmanageable proportions. Only in those rare instances where advance warning of a tanker spill is provided, or for long discharge periods, is there a meaningful role for these offshore devices, and only if the sea conditions are relatively calm. Finally, it is very clear that conventional booms and skimmers have no role in any spill situation involving ice.

In summary, large offshore oil spill containment barriers and recovery devices (and their ancillary equipment including pumps, barges, etc.) have a limited application for Canadian offshore spills. It should be emphasized that this is not the case for smaller equipment used to protect sensitive shorelines and to corral and pick up oil in quiescent inshore areas. Easily deployable and inexpensive inshore booms and skimmers that can process viscous oily liquids can be very useful in dealing with major offshore oil spill situations where oil comes shoreward.

### Dispersants

Unlike physical recovery techniques, chemical dispersion methods appear to be technically attractive for most of the no-ice scenarios considered in this study. They are particularly appealing for blowouts, because such spills are generally thin and fresh, and for fresh spills in choppy seas, because such ocean conditions assist in the oil dispersion process. For tanker spills, however, dispersant technologies are almost as limited as others because of the response-time problem discussed earlier; they are also not effective in situations where the oil spill is in the form of a water-in-oil emulsion (Case No. 5) or a partially-burned oil (Case No. 1).

In this paper, the issue of the environmental acceptability or advisability of using chemicals to treat offshore oil spills has not been addressed. This issue, however, is not unimportant. Unlike physical recovery, which offers a "motherhood" approach to the spill cleanup problem in that oil is largely removed from the natural environment, the use of chemicals presents difficult decision-making challenges. If an offshore oil spill is not dispersing naturally but might disperse if chemicals were added, it becomes necessary to decide whether it is in the interest of overall environmental protection to apply dispersants. If the oil remains on the surface and cannot be physically recovered, it will threaten birds, shorelines, marinas, and other resources exposed to the water surface. If that threat is removed by chemical dispersion, resources in the water column are at risk.

The situation, of course, is never black and white. It is possible to have a mix of countermeasures techniques depending on the circumstances of the spill: physical recovery during periods of calm, and natural dispersion and even some chemical application during rougher conditions. But, the decision to use or not to use chemical dispersants forces one to come to grips with the entire issue of oil spill impact. The rational use of dispersants requires a high level of understanding of the fate, behaviour and effects of both treated and untreated oil spills. In dealing with major offshore oil spills in Canada, acceptance of dispersants as a viable treatment option may be one of the most important questions to be resolved in providing an acceptable overall level of environmental protection.

## CONCLUSIONS

### Overall Major Conclusions

A range of oil spill possibilities exists for the Canadian offshore environment over the next decade. All possibilities can be classified generally into combinations involving spill type (tanker spill vs blowout); discharge period (short vs long); ice conditions (no ice, complete ice cover and partial ice cover); sea state (low or high); and water depth (shallow or deep). In general, one can conclude that:

a) oil spills from blowouts are easier to control than those from tankers;

b) spills occurring in a complete ice cover environment, whether blowouts or tanker spills, are relatively straightforward to control by means of in situ combustion or other techniques;

c) dispersants have a great potential for use in many open water oil spill situations, especially in ocean conditions which are too rough for mechanical containment and recovery techniques and where ocean mixing is already causing some natural dispersion of the oil. Shallow-water oil blowouts probably form water-in-oil emulsions which are not chemically dispersable; however, deep-water blowouts can be effectively treated with chemical dispersants;

d) no proven or tested technology exists which can efficiently remove oil from a partial ice cover environment;

e) in a rough, open water situation, little can be done at source with the current state-of-the-technology to deal with oil quickly released from a tanker spill.

### Risk of Tanker Spills

Large batch spills, especially accidental discharges from medium-to-large crude tankers, represent the greatest oil spill risk to Canada over the next decade. This is due to the fact that tanker spills are more likely to occur than other kinds of offshore spills (e.g., blowouts) and are much more difficult to control.

A review of world-wide oil spill statistics would provide very strong evidence that tanker oil spills are far more frequent than oil spills from blowouts. For spills larger than, say, 10,000 $m^3$, perhaps ten times more tanker spills have occurred historically than offshore oil blowouts. Additionally, a) an existing large volume of tanker traffic flows into eastern Canadian ports; b) Canada's two largest offshore oil spills occurred from tanker accidents off the east coast; and c) Hibernia and Beaufort oil production plans include proposals to transport processed oil via large tankers to the east coast. The conclusion is that the probability of a major offshore oil spill from a crude carrier, especially off the east coast, is high relative to other spill types, and will likely increase in the future once Canadian undersea oil is produced.

### Controlling Tanker Spills

More specific to this study is the conclusion that tanker spills generally are extremely difficult to control at source. The major cause of the problem is that, although technologies for dealing with offshore spills do exist, it is very difficult to implement a fast enough response to a large marine oil spill before extensive oil spreading and weathering occur. For example, for existing dispersants to be effective against a 35,000 $m^3$ tanker spill discharged over a 1-day period, they must be applied to the oil spill while it is still fresh, generally less than a day after the oil's release. Large aircraft (DC-6 type) and dispersant stockpiles (upwards of 2,500 $m^3$) would have to be permanently dedicated and manned at strategic locations across Canada to accomplish this. The enormous cost of doing this is considered prohibitive.

Any factor associated with a tanker accident that allows for more time to respond, or which decreases the oil discharge rate or the rate of spread of oil, is beneficial to the cleanup process. Such factors do indeed present themselves, but they are beyond the control of the oil spill fighter. For example, if a tanker spill occurs in a complete ice cover environment, the spreading and aging of the oil is drastically reduced; the response need therefore not be instantaneous to be effective. For tanker accidents that occur in open water, where the circumstances are such that a large oil discharge is not immediately produced but occurs some time after the accident, or when the oil discharge rates are relatively low, an effective response becomes possible as well with existing technology and capability. In general, however, these kinds of accidents are rare.

### Controlling Oil Blowouts

Except for the environmental conditions of partial ice cover or high seas (combined with the formation of water-in-oil emulsions), all possible oil well blowouts that could take place in Canada have the potential to be effectively controlled. In general, if the subsea blowout takes place in fairly deep waters, it is likely that the oil slick on the water surface will be thin and fresh and easily dispersable by natural forces or by the application of chemical dispersants. Shallow-water blowouts, like the Ixtoc I blowout, however, are likely to form water-in-oil emulsions which are not dispersable but, weather permitting, they can be controlled by mechanical containment devices followed by in situ burning or skimming. As mentioned, shallow subsea blowouts taking place under a stationary or moving complete ice cover are relatively amenable to control because the oil is contained and preserved in the ice until springtime, when an igniter deployment operation can be initiated to burn the oil as it emerges on the ice surface.

### Arctic vs Southern Spills

In general, the technological capability to clean up a major spill in the Arctic is not radically different from that in southern Canada. On the one hand, the presence of ice cover for much of the year is an asset in dealing with a spill. The removal of a high percentage of oil from a blowout or tanker spill is technically feasible under winter ice conditions. On the other hand, a northern oil spill cleanup operation has obvious logistical and environmental difficulties which would hamper a countermeasure operation: first, there is a severe lack of local manpower available; second, land-based transportation is non-existent, and the distances between major southern centres and northern air fields, and between the northern communities and possible spill sites are large; third, the accommodation and servicing of large work forces in the North will be more difficult than in the southern regions of Canada; and finally, the Arctic climate can be much more severe than in the south. The technological ability to respond to a northern spill may be equivalent to a southern operation, but these additional problems necessitate a much more complex support organization and planning structure.

## RECOMMENDATIONS

An attempt has been made to identify, from a national perspective, priority areas that should be addressed over the next decade to improve the country's state of preparedness to deal with major offshore spills. The recommendations are directed toward those in government and industry who have national responsibilities or programs in the area of oil spill countermeasures. It is obvious that priority should be given to those potential spills that present the greatest risk to Canada in terms of their probability and their likely impacts.

### General, High Priority Areas

It is recommended that the following general areas be given special attention over the next decade.

**East Coast Tanker Spills.** Tanker spills, especially those on the east coast, should be the highest priority area for government oil spill control agencies, as it was several years ago before interest, activity and funds were diverted toward the oil well blowout problem. Oil companies with a particular interest in the potential tanker traffic associated with Beaufort and Hibernia oil production should also consider this to be of high priority. Canadian industry involvement in this area of activity is believed to be especially important since credible oil spill control programs and capabilities, developed for oil well blowouts, already exist in industry and would have much application vis-a-vis tanker spills. Furthermore, significant oil industry activity in the area of tanker spill control would do much to fill the vacuum created by the inactivity of non-Canadian companies which own the tankers presently entering Canadian ports (many are "one-ship" companies). These companies generally do not have the capability of cleaning up spills associated with their tankers. Fortunately, this will probably not be the case for Beaufort and Hibernia oil tankers.

**Government/Industry Contingency Planning.** In the event of a major offshore oil spill in Canada, the countermeasures resources of the entire country would probably be accessed and taken advantage of in some manner or other. For example, a major oil well blowout on the Grand Banks or in the southern Beaufort Sea would see, in addition to company personnel and resources, the immediate involvement of government groups, equipment and advisors from other companies, and perhaps even resources from other countries. This must be reflected in detailed joint government/industry contingency planning.

It is worth emphasizing that contingency planning and training efforts are at least equally as important as technological development efforts. There is no adequate substitute for experienced personnel who are familiar with the operation of the latest response equipment under offshore conditions. Particular training is required for relatively unfamiliar and difficult areas like the Arctic. Since, in the actual events, government and industry personnel will most likely be working together, it is advisable that pre-spill training and contingency planning programs be jointly conducted.

**Two Major Countermeasures Problems.** The two most serious challenges facing the oil spill fighter in Canada, as identified in this paper, are "response-time" and "partial-ice". For most batch spills that occur in open water, the major countermeasures question is how to deliver those technologies known to be effective to the spill site prior to the oil's spreading and weathering beyond control. It is recommended that priority be given to creative thinking and attempts to solve this vexing problem. Perhaps studies should be conducted to determine the feasibility of using Hibernia and Beaufort tankers as working platforms for countermeasures operations; feasibility studies could be conducted on the establishment of a national strike force (government/industry?), well equipped with appropriate equipment and materials, to respond within a few short hours to Canadian offshore tanker spills; or, more effort should be invested in researching novel approaches to the problem, such as in situ burning for tanker spills, use of the void space between double hulls for storage of dispersants or solidifying agents, etc.

With regard to the "partial-ice" issue, similar creative efforts should be dedicated towards solution of the problem. For both problems, the chances of successfully developing practical answers seem low, but their seriousness relative to other oil spill control problems is high, and the effort is warranted.

Of the above two problems, the "response-time" is far more important, as it is prevalent to most batch spill situations including a tanker spill in a partial ice environment and should take on higher priority.

**Dispersants.** The most promising countermeasures technique that has been identified for most open water major spills in Canada involves the use of dispersants. Every effort should be made to take advantage of one of the few cleanup measures that actually works under many circumstances. Because there is much room for improvement, however, several specific areas for dispersant research or planning are recommended, as described below.

### Specific, Recommended Projects

The following is a list of recommended projects to be performed over the next few years. The list is not intended to be complete, and the projects are not listed in order of priority.

a) Government dispersant use guidelines should be established to permit fast, accurate and environmentally appropriate decisions to be made at the time of a spill;

b) more work is required on the details of the logistics for using dispersants for Canadian offshore spills;

c) the feasibility of applying dispersants, from supplies kept on board Arctic and Hibernia tankers, directly from the tanker deck onto the escaping oil should be studied. Application techniques, dispersant transfer problems on the tanker, and dosage control all require review;

d) research should continue into the development of new dispersants which are effective on viscous oils so that they may be more useful in Canadian applications;

e) the advisability of stockpiling massive quantities of dispersant at strategic locations in Canada (e.g., Tuktoyaktuk, St. John's) should be investigated. The advisability of using dispersants on a Hibernia blowout/oil spill, which otherwise would not threaten Canadian coastlines, should also be investigated;

f) the action and feasibility of injecting dispersants into the oil/gas plume of a subsea blowout, either at the seabed or in the high mixing zone near the surface, should be investigated.

**Burning Oil on Open Water.** Research on the combustibility of thick oil slicks present on open water or contained by a partial ice cover should be undertaken.

**Dispersion vs Emulsification.** A better understanding of the competing processes of oil dispersion and emulsification is needed to allow better predictions of oil behaviour and fate to be made. This will then assist in designing realistic oil cleanup operations. More knowledge is also required on the conditions under which subsea oil well blowouts form water-in-oil emulsions.

**Arctic Shoreline Cleanup.** A detailed analysis of the feasibility and logistics of extensive Arctic operations for shoreline cleanup and oiled debris disposal is required.

**Tanker as Work Platform.** Studies should be conducted to determine the feasibility of using large Canadian oil tankers as working platforms for countermeasures operations. Crew safety, ship stability and safety, operator acceptance, and personnel requirements are some of the factors to consider in such a study. The feasibility of deploying men and spill response equipment over the side of such tankers to attempt to contain and remove escaping oil at the source should also be investigated. This study would necessarily include the review of potential methods for containing, collecting and transferring the collected oil to suitable storage on board the damaged vessel.

**Logistics of Igniter Operation.** The logistics of an igniter operation for a tanker spill taking place under conditions of a complete ice cover should be determined.

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# ASSESSMENT OF DAMAGE FROM OIL SPILLS

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## INTRODUCTION

The consequences of oil spills at sea have been the subject of a large number of studies. Although recent work indicates that the environmental damage often is less disastrous than was commonly believed some years ago, the harmful effects are certainly considerable in many cases. Estimates of costs per ton of oil vary enormously, ranging from $34,000 to $35,000 (U.S.), including both cleanup and damage claims, as indicated in a survey of eight larger spills (White and Nichols, 1981). This variation is partly related to factors such as the nature of the oil, the location of the spill, and cleanup policy, but also reflects, to a large extent, the difficulties we are faced with in assessing environmental damage and in giving a reasonable cost of this damage.

This paper deals primarily with the problem of assessing and comparing oil spill damage types, some of which are, at the outset, apparently noncomparable. The presentation is based on reports from the Central Institute for Industrial Research, Oslo, on this subject (Fredrikson et al., 1982; Central Institute for Industrial Research, 1983).

The work reported is part of a more comprehensive study aimed at improving both the preparedness for coping with oil pollution (i.e., strategy) and oil spill combat operations. A system for a total cost-benefit analysis of proposed strategies has been developed (Central Institute for Industrial Research, 1983) and includes models that predict the risk of various oil spills, describe the fate of oil and results of proposed combat actions, estimate combat action costs, and describe environmental and economical damage from oil spills. The final step in the total decision analysis is based on multi-attribute utility analysis; the results from the various models are used as input parameters.

## MULTI-ATTRIBUTE UTILITY ANALYSIS

We are faced with two problems areas in decision analysis. We must develop a method to estimate the extent of ecological or economical damage. We must also develop a method to evaluate the overall damage by means of some comprehensive measure which can be related to combat costs. In principle, it should be possible to give objective estimates of damages; evaluation, however, will depend on the decision-maker's preferences.

The multi-attribute utility theory developed by Keeny and Raiffa (1976) is a promising method for damage assessment when value preferences must be taken into account. The method includes a convenient way to structure the problem and provides us with an effective tool in the analysis of the relative importance of the parameters which influence the decisions.

## UTILITY FUNCTIONS

In order to apply the techniques of multi-attribute utility analysis, the problem must be structured in a convenient way. Various "objectives" may be given, as shown in Figure 1. The overall broad objective of oil pollution contingency planning is to "find" the best action. To carry out a meaningful analysis, this rather vague objective must be broken down into more concrete objectives, as indicated in Figure 1. The objectives at the bottom of the hierarchy may be characterized by simple physical measures, such as days, km, or monetary terms. These measures are denoted attributes.

For each of the attributes, a relationship between "utility" (a number between 0 and 1) and consequence (attribute value) must be established. If the decision-maker is risk-neutral, the function is linear. The decision-maker may, however, be risk-averse or risk-prone (see Figure 2). In the following pages, we have generally assumed risk neutrality, although in some cases there may be arguments for using non-linear relationships.

The functions given in Figure 2 apply to one consequence (or attribute) and may be called a primitive utility function; they must be combined into a total utility function. With three variables, the total utility function may, assuming that certain conditions are fulfilled, be written as:

$$U(x_1,x_2,x_3) = k_1u_1(x_1)+k_2u_2(x_2)+k_3u_3(x_3)+kk_1k_2u_1(x_1)u_2(x_2)+$$

$$kk_1k_3u_1(x_1)u_3(x_3)+kk_2k_3u_2(x_2)u_3(x_3)+k^2k_1k_2k_3u_1(x_1)u_2(x_2)u_3(x_3)$$

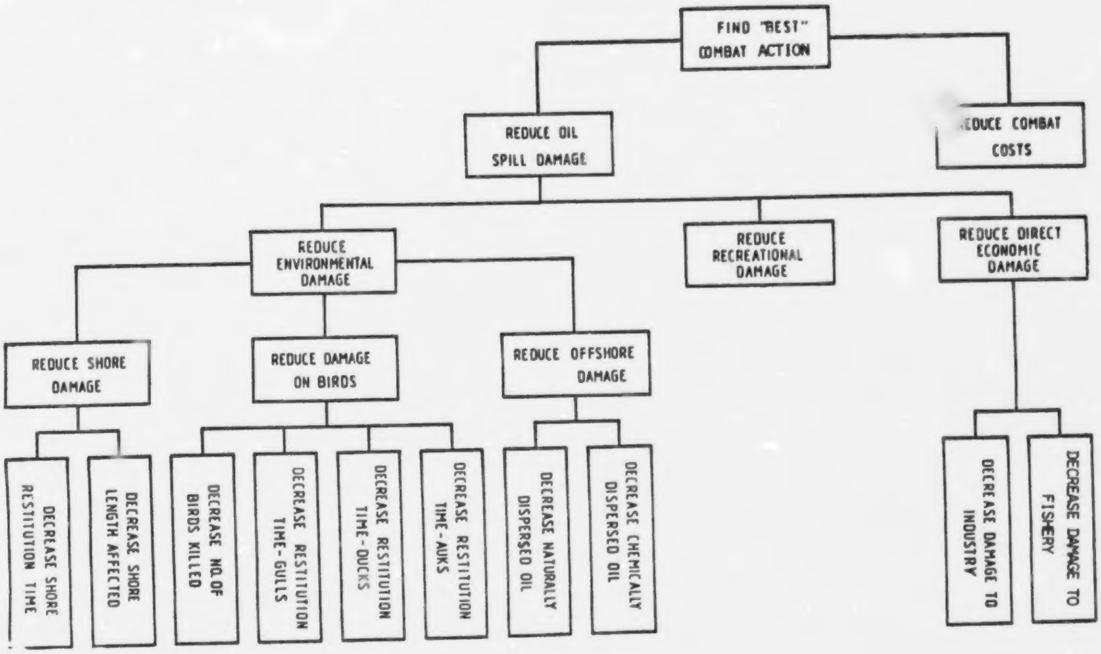

FIND "BEST" COMBAT ACTION
REDUCE OIL SPILL DAMAGE
EDUCE COMBAT COSTS
REDUCE ENVIRONMENTAL DAMAGE
REDUCE RECREATIONAL DAMAGE
REDUCE DIRECT ECONOMIC DAMAGE
REDUCE SHORE DAMAGE
REDUCE DAMAGE ON BIRDS
REDUCE OFFSHORE DAMAGE
DECREASE SHORE RESTITUTION TIME
DECREASE SHORE LENGTH AFFECTED
DECREASE NO.OF BIRDS KILLED
DECREASE RESTITUTION TIME-GULLS
DECREASE RESTITUTION TIME-DUCKS
DECREASE RESTITUTION TIME-AUKS
DECREASE NATURALLY DISPERSED OIL
DECREASE CHEMICALLY DISPERSED OIL
DECREASE DAMAGE TO INDUSTRY
DECREASE DAMAGE TO FISHERY

FIGURE 1 STRUCTURE OF THE VALUE MODEL

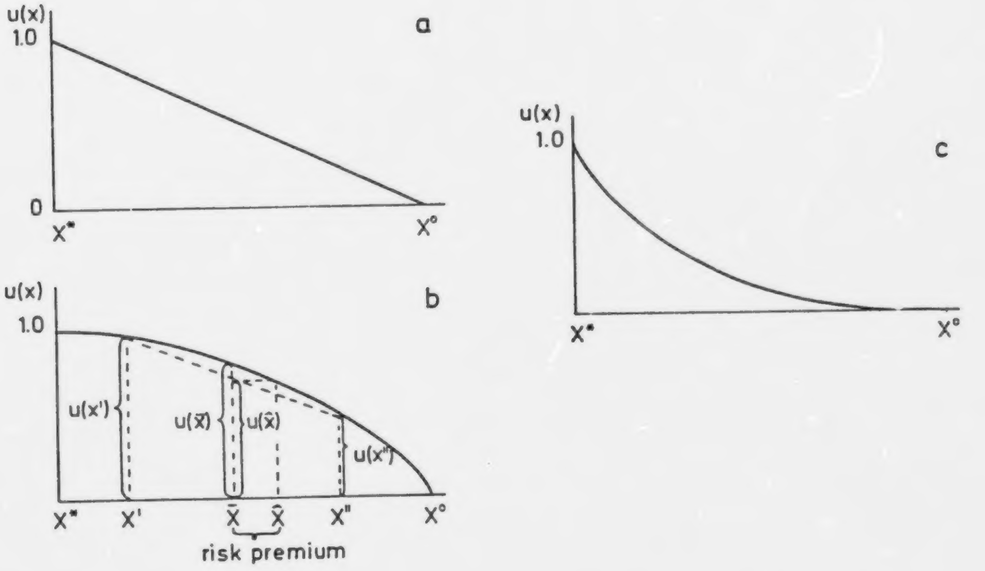


FIGURE 2 UTILITY AS A FUNCTION OF CONSEQUENCE, X. X* IS THE MOST PREFERRED AND X° THE LEAST PREFERRED CONSEQUENCE

a: A linear utility function
b: A risk-averse utility function; the decision-maker is willing to pay to avoid the uncertainty associated with a lottery
c: A risk-prone utility function; the decision-maker prefers the risk associated with a lottery

Generalization to n variables is straightforward. To establish this function, it is necessary to determine primitive utility functions (i.e., $u_1(x_1)$, $u_2(x_2)$, $u_3(x_3)$); scaling constants (i.e., $k_1$, $k_2$, $k_3$); and a synergy coefficient, k. If $k = 0$, we have an additive utility function, with scaling constants $k_1$, $k_2$ and $k_3$ reflecting the decision-maker's opinion of the importance of the individual attributes:

$$U(x_1,x_2,x_3) = k_1u_1(x_1) + k_2u_2(x_2) + k_3u_3(x_3)$$

k may be in the range $(-1,\infty)$. If $k < 0$, the total utility is less (or equal if all u's except one are 0) than the weighted sum of the primitive utility functions.

The constants ($k_1$, $k_2$, $k_3$ and k) are, in principle, determined by asking the decision-maker to compare different consequences by answering certain lottery questions. Various interest groups may be asked to get an idea of the variations in preference values. It may be difficult to obtain people's real preferences by such questions; the results should therefore be compared with those obtained by other methods. A computer program is available for obtaining the necessary constants and computing utilities.

We will present results based on answers from two reference groups: U1 represents the opinion of the Norwegian State Pollution Authorities, while U2 represents the opinion of the steering committee of the project. The total utility functions, U1 and U2, are given in Table 1. The two groups representing decision-makers differed in their weighting of some of the consequences. Thus, the ratios of environmental damage to exposures (recreation) to economical loss are 1:1:3 in U1 and 1:2:2 in U2. Furthermore, of the environmental parameters, bird damage is most strongly emphasized in U2, while offshore damage is given significant weight in U1. It should also be observed that in U1, naturally dispersed oil is much more serious than chemically dispersed oil, while in U2 the opposite weighting is given. These differences seem to be due to real differences in opinion between the groups; the analysis has thus been carried out for both alternatives.

TABLE 1 ESTABLISHED CONSTANTS ($k_i$) AND SYNERGY COEFFICIENTS (k) OF THE UTILITY FUNCTIONS

| | | Constants ($k_i$) | |
|---|---|---|---|
| Name of Component Utility Function | Variables | U1: Norwegian State Pollution Authorities (SFT) | U2: Project Steering Committee |
| TOTAL | DAMAGE | 0.64 | 0.726 |
| | COMBAT | 0.36 | 0.274 |
| | k | 0 | 0 |
| DAMAGE | ENVIRON | 0.24 | 0.211 |
| | EXPOSURES | 0.20 | 0.412 |
| | LOSS | 0.61 | 0.4224 |
| | k | -0.16 | -0.137 |
| LOSS | INDUSTRY | 0.485 | 0.5 |
| | FISHERY | 0.515 | 0.5 |
| | k | 0 | 0 |
| ENVIRON | SHORE | 0.158 | 0.128 |
| | BIRD | 0.65 | 0.843 |
| | OFFSHORE | 0.28 | 0.03 |
| | k | -0.277 | 0 |
| OFFSHORE | NATDISP | 0.75 | 0.31 |
| | ARTDISP | 0.20 | 0.75 |
| | k | 0.26 | -0.27 |
| BIRD | DEATHS | 0.432 | 0.743 |
| | GULLREST | 0.0561 | 0.034 |
| | DUCKREST | 0.6494 | 0.4095 |
| | AUKREST | 0.9775 | 1.0 |
| | k | -0.996 | -0.996 |
| SHORE | SHOREREST | 0.969 | 0.995 |
| | LENGTH | 0.99 | 0.976 |
| | k | -0.996 | -0.996 |

The best combat action corresponds to the highest value of total utility. In our studies, we have defined the optimum combat action as the action which maximizes the willingness to pay. This is not necessarily equal to finding the highest value of total utility, though Fredrikson et al. (1982) found that the difference was probably not of critical importance for oil spill problems.

## DAMAGE PARAMETERS (ATTRIBUTES)

Table 2 presents attributes describing damage caused by oil spills. The first eight damage attributes are ecological parameters, while the remaining three are related to human activities. The final attribute in the total function is combat costs. Upper and lower limits must be chosen for each attribute (Xi) to specify our working domain. The limits given in Table 2 are based on data from historical oil spills. The upper limits refer to an oil spill of about 150,000 metric tons (i.e., a large but not catastrophic event). The oil is assumed to be of medium toxicity.

TABLE 2 ATTRIBUTES WITH THE CORRESPONDING LIMITS USED IN THIS ANALYSIS

| Attribute Number | Description | Name | Unit | Limits |
|---|---|---|---|---|
| X1 | Shore restitution time | SHOREREST | years | 0.02 - 15 |
| X2 | Shore length affected | LENGTH | kilometres | 0.1 - 300 |
| X3 | Number of birds killed | DEATHS | (number) | 100 - $2.5 \times 10^6$ |
| X4 | Restitution time, "gulls" | GULLREST | years | 0.1 - 5 |
| X5 | Restitution time, "ducks" | DUCKREST | years | 0.1 - 25 |
| X6 | Restitution time, "auks" | AUKREST | years | 0.1 - 50 |
| X7 | Amount of oil dispersed naturally | NATDISP | metric tonnes | 0.1 - 100,000 |
| X8 | Amount of oil dispersed by chemical means | ARTDISP | metric tonnes | 0.1 - 100,000 |
| X9 | Recreational "visits" hindered by oil production | EXPOSURES | (people) x (days) | 100 - $5 \times 10^6$ |
| X10 | Damage costs, industry | INDUSTRY | mill. NOK | 0 - 500 |
| X11 | Damage costs, fishery | FISHERY | mill. NOK | 0 - 500 |
| X12 | Total combat costs | COMBAT | mill. NOK | 0 - 1,000 |

### Shore Damage

Shore damage is expressed by X1 and X2. X1, shore restitution time, expresses the ecological damage caused by the oil reaching the shore. This attribute will depend on the type of shore (rocky, sandy, marshy), as well as on energetic conditions (waves, tides) and biological vulnerability. Restitution time is not given a precise definition but should reflect the time necessary to obtain a shore community with a diversity comparable to the situation prior to the oil spill. The maximum value of 15 years restitution time will only be observed for the most vulnerable shore types, such as sheltered, marshy areas.

X2, shore length, expresses the extent of damaged shore. If the amount of oil is above a certain limit (say 4 kg/m$^2$), "total" damage may be assumed. A suitable function may be constructed to describe the relative damage for lower values.

### Damage to Birds

Damage to birds is expressed by the number of birds killed (X3), irrespective of species, and the restitution times for three groups of birds, denoted by "gulls", "ducks", and "auks". (The groups include species not actually belonging to these families).

X4, restitution time - gulls, includes species with a high reproduction rate (e.g., gannets, fulmars and cormorants), in addition to species belonging to *Laridae*. The restitution time should not likely be more than 5 years.

X5, restitution time - ducks, includes species vulnerable to oil pollution, but with a high reproduction potential (e.g., divers), in addition to species belonging to *Antidae*. The maximal restitution time is set at 25 years.

X6, restitution time - auks, includes species vulnerable to oil pollution and with a low reproduction potential (e.g., puffins, razorbills and guillemots). It is assumed that the restitution time may be up to 50 years.

### Offshore Damage

Offshore damage (excluding damage to commercial fisheries, see X11) is expressed by two proxy attributes: X7, the amount of oil dispersed naturally; and X8, the amount of oil dispersed by chemical means.

Damage to the life in the ocean is difficult to measure. Fortunately, it is not likely to be of critical importance (Clark, 1982) and probably is of little significance; possible damages are simply assumed proportional to the amount of oil dispersed. Chemically dispersed oil is considered separately, but similarly, to naturally dispersed oil.

### Recreational Damage

X9 expresses the loss of reactional possibilities such as swimming, camping, angling and boating. It is measured as follows:

X9 = (No. of people affected) x (No. of days)

### Direct Economical Damage

Economical damage is expressed by two attributes. X10, damage costs - industry, expresses economical costs related to cleaning of harbours and boats, production loss due to hindrance of transport, loss of income from tourism, damage of property, and loss of income in other areas due to postponed deliveries from industry in the polluted area.

X11, damage costs - fishery, expresses economical loss connected with commercial fishery, such as reduction in fish stocks, damage to fishing gear and aquacultures, and catch loss due to delays.

### Combat Costs

X12 includes only direct costs of a combat action.

## APPLICATIONS

The approach to damage assessment and decision analysis described in the previous sections is illustrated in some examples presented below.

### The Drupa Oil Spill

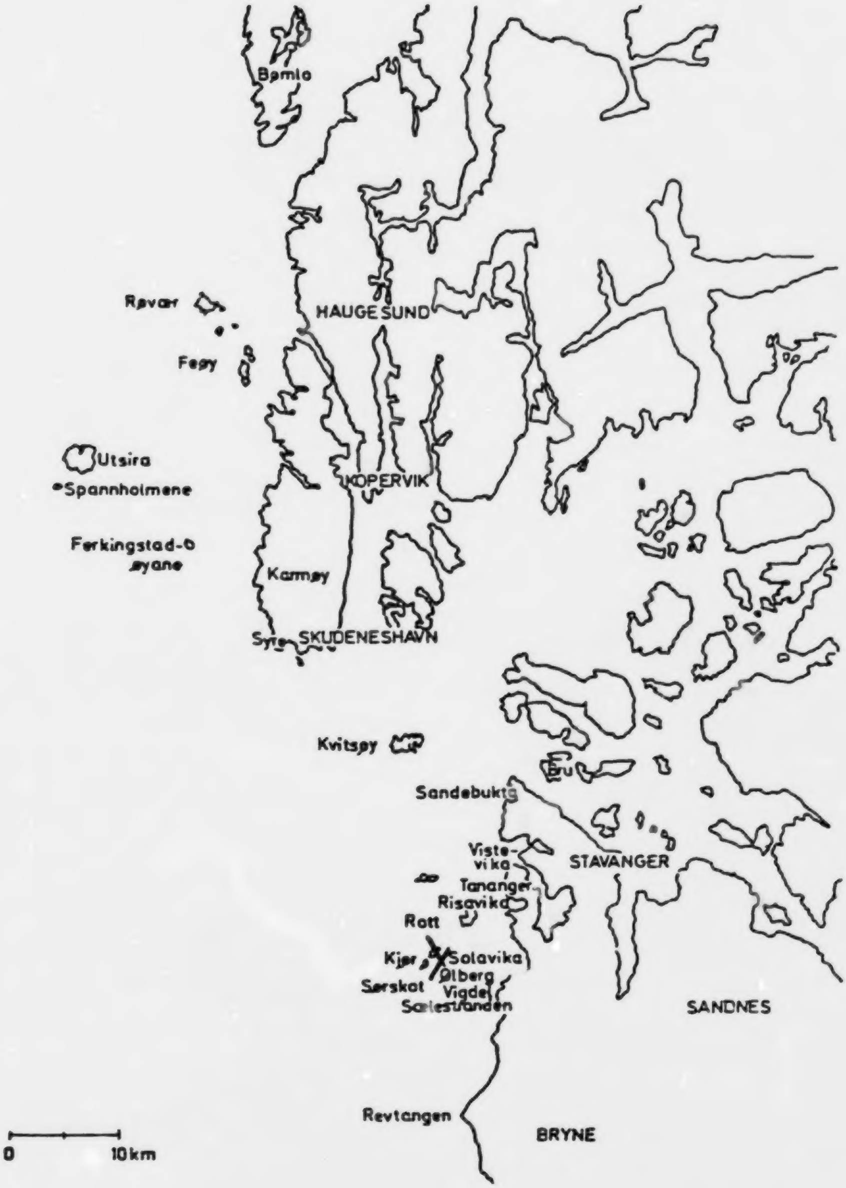
This example is an historic event. A tanker on its way to refineries at Risavika, Southern Norway (see Figure 3) ran aground in February, 1976; approximately 2,500 tons of oil were discharged.

The affected shoreline is primarily located in Rogaland, south of Karmoy, but oil slicks were observed as far north as Rovaer. The shores of South-Rogaland consist of several sandy beaches and muddy/marshy regions. The shores further north are comparatively more rugged and typically high energetic.

The incident occurred in winter-time. Comparatively few birds were damaged, despite the fact that a large number of birds (particularly ducks and auks) have their winter-quarters in South-Rogaland.

The estimated recreational consequences were rather large, reflecting the year-round angling activity; some of the affected shores also were coated with oil the following summer, hampering the recreational activities in general.

The estimated damage picture, as described in our model, is presented in Table 3, column S1. S2 is the damage picture that corresponds to a hypothetical combat action which would have reduced all the attributes to their minimum values. The willingness to pay for such an action (equal to the economical value of all damages that actually occurred) has been estimated for the two reference groups. The values reflect the groups attitudes (values) towards the seriousness of the reported damages.


Bømlo
Røvær
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•Spannholmene
KOPERVIK
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STAVANGER
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Kjør
X
Solavika
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Sørskot
Vigdel
Sølestranden
SANDNES
Revtangen
BRYNE
0
10km

FIGURE 3 THE DRUPA OIL SPILL AREA. THE LOCATION OF THE SPILL IS MARKED BY X.

Reference group 2 is willing to pay 128 mill. NOK to avoid the damage, while group 1 is willing to pay only 51.6 mill. NOK. Recreation is weighted more heavily in U2; and this difference in opinion between the two groups explains the difference obtained in the willingness to pay, i.e., the felt seriousness of the observed damage.

Actions such as beach-cleaning, removal of dead birds, and cleaning of damaged ones were undertaken after the accident, to a total cost of 10 mill. NOK. In addition, voluntary contributions were considerable. The actual damage reduction achieved has not been estimated, but the costs of these actions are well below the estimated willingness to pay.

TABLE 3 THE DRUPA OIL SPILL. ESTIMATED DAMAGE WITHOUT ACTION AND MINIMUM DAMAGE (S2), WITH CORRESPONDING FIGURES FOR THE WILLINGNESS TO PAY (IN MILL. NOK)

| | | | | Willingness to Pay | |
|---|---|---|---|---|---|
| Variable | S1 | S2 | Units | SFT | Project Steering Committee |
| SHOREREST | 5 | 0.02 | years | 5.9 | 8.8 |
| LENGTH | 120 | 0.1 | km | 6.3 | 8.5 |
| DEATHS | 2 | 0.1 | numbers | 0.002 | 0.015 |
| GULLREST | 0.5 | 0.1 | years | 0.006 | 0.02 |
| DUCKREST | 2 | 0.1 | years | 0.17 | 0.3 |
| AUKREST | 5 | 0.1 | years | 1.78 | 6.53 |
| NATDISP | 800 | 0.1 | ton | 0.52 | 0.03 |
| ARTDISP | 0 | | | 0 | 0 |
| EXPOSURES | 500 000 | 100 | people x days | 30.9 | 100.3 |
| INDUSTRY | 10 | 0 | mill. NOK | 9.8 | 10.3 |
| FISHERY | 2 | 0 | mill. NOK | 2.1 | 2.1 |
| Total willingness to pay | | | | 51.61 | 128.0 |

### Blow-out at the Brisling Field

This example is a hypothetical scenario. An underwater blowout at the Brisling field, southwest of Stavanger, Southern Norway, is assumed to dischage 26,000 tons of oil (see Figure 4). The affected area consists of several islands primarily with high energy shores. Some stretches of shoreline have shallower waters with longer restitution times. The area has a scattered bird population, but no known area of particular vulnerability. The estimated damage picture is presented in Table 4, column S1. The event is assumed to occur in the summer. A combat action based on normal operation equipment (skimmers and booms) under fair weather conditions has been considered and modeled. The cost of this action has been estimated at 11 mill. NOK. The proposed action would lead to reductions in the amount of oil reaching the shores which are too small to have a significant effect on the damage-picture. The only benefit is therefore a reduction in offshore damage.

The result of this action is presented in column S2 of Table 4. The willingness to pay for this action is rather low for both reference groups. The proposed action is far from being cost-effective. However, if an action was carried out that led the oil away from vulnerable areas, in this case by preventing the oil slick from drifting southwards towards Bomlo-Stord after reaching the shores, then an action may be cost-effective. The result of such an action is presented in Table 4, column S3. The willingness to pay for this action is comparable to the proposed action costs, although reference group 1 is less willing to pay than group 2, again reflecting the smaller emphasis group 1 has given to recreational damage compared with group 2.

## CONCLUDING REMARKS

Multi-attribute utility analysis provides an effective tool for evaluating different strategies and combat operations in connection with oil pollution. The systematic manner in which the overall goal is broken down to measurable attributes represents a sound and convenient way of approaching problems of this kind.

The examples presented in this paper have illustrated how this technique may be used to assess damage and evaluate combat actions in specific cases. It must be admitted that the estimation of physical and ecological damages is too subjective in this work. For more general applications, we have tried to improve this by developing a computerized evaluation scheme of resources along the Norwegian coast.

It has not been possible to discuss the uncertainties in the attribute values here. This is, however, an important point. Some preliminary calculations have been made using probability distributions instead of fixed values for some parameters, an approach which should be used in further work.

In spite of the obvious shortcomings at the present stage of development, we believe our approach to be a very promising one. The main advantage is that the value preferences and risk attributes of a person (or persons) are quantified through the utility function. In any multi-objective problem area where trade-offs have to be made between benefits and (uncertain) damages, these preferences are implicit when major decisions are taken (e.g., on the level o preparedness to be established to fight oil pollution).

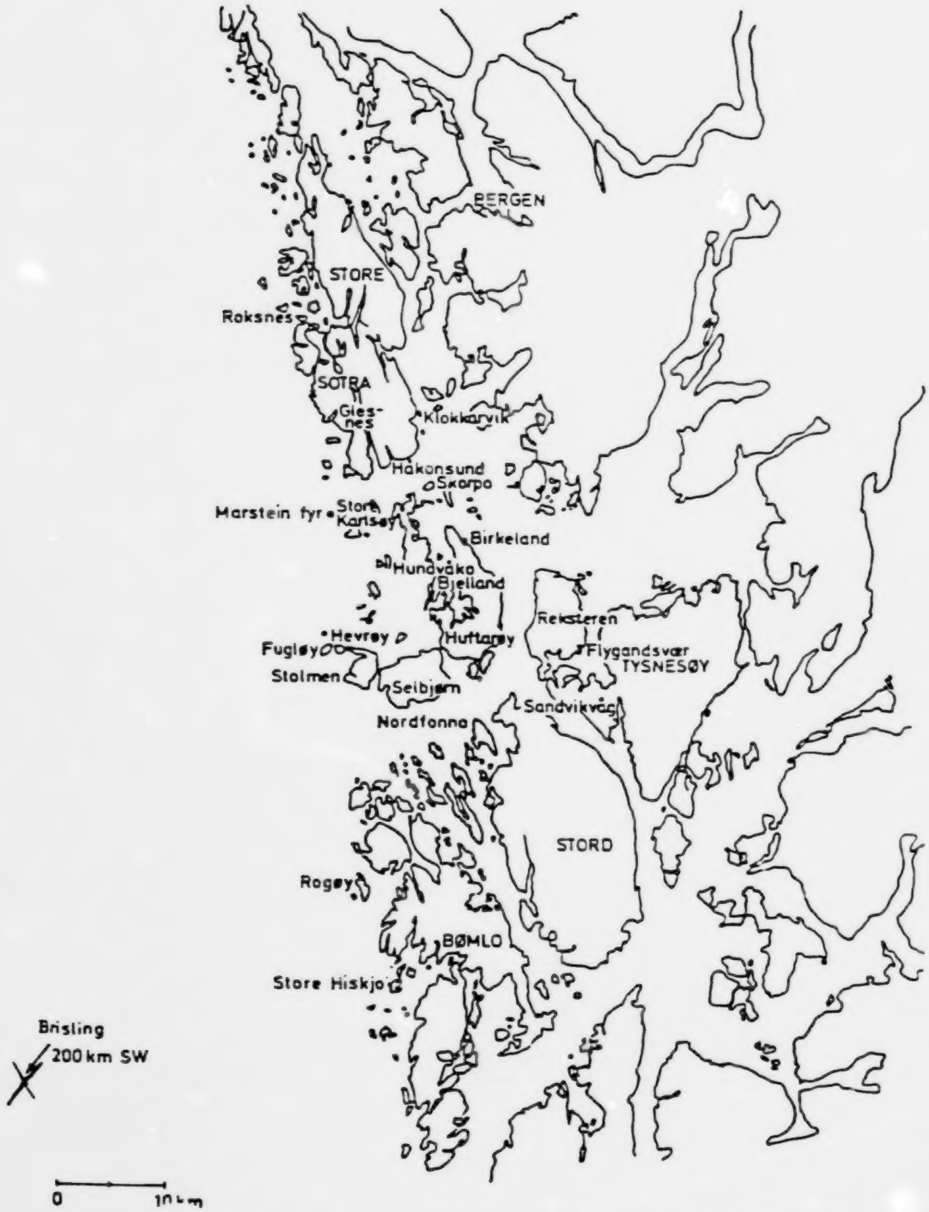
BERGEN
STORE
Roksnes
SOTRA
Gles-nes
Klokkarvik
Håkonsund
Skorpo
Marstein fyr
Store Kartsøy
Birkeland
Hundvåka
Bjelland
Reksteren
Hevrøy
Fugløy
Huftarøy
Flygandsvær
TYSNESØY
Stolmen
Selbjørn
Sandvikvåg
Nordfonna
STORD
Rogøy
BØMLO
Store Hiskjo
Brisling
200 km SW
0
10 km

FIGURE 4 BRISLING FIELD BLOWOUT AREA. THE LOCATION OF THE BLOWOUT IS INDICATED (X)

TABLE 4 THE BRISLING FIELD BLOWOUT. ESTIMATED DAMAGE WITHOUT ACTION (S1), WITH A NORMAL OIL COLLECTION ACTION AT THE SITE (S2) AND WITH A HYPOTHETICAL ACTION AIMED AT PREVENTING DAMAGE IN VULNERABLE AREAS (S3), WITH CORRESPONDING FIGURES FOR THE WILLINGNESS TO PAY (IN MILL. NOK)

| | | | | | | | Willingness to Pay | |
|---|---|---|---|---|---|---|---|---|
| Variable | Unit | S1 | S2 | U1 | U2 | S3 | U1 | U2 |
| SHOREREST | years | 3 | 3 | | | 2.5 | 0.98 | 1.41 |
| LENGTH | km | 201 | 201 | | | 135 | 2.22 | 2.80 |
| DEATHS | numbers | 9 450 | 9 450 | | | 6 835 | 0.005 | 0.05 |
| GULLREST | years | 3.1 | 3.1 | | | 3.1 | 0 | 0 |
| DUCKREST | years | 6 | 6 | | | 6 | 0 | 0 |
| AUKREST | years | 12 | 12 | | | 12 | 0 | 0 |
| NATDISP | ton | 9 500 | 8 000 | 0.31 | 0.06 | 8 000 | 0.31 | 0.06 |
| ARTDISP | ton | 0 | 0 | | | | 0 | 0 |
| EXPOSURES | people x days | 200 000 | 200 000 | | | 100 000 | 6.18 | 20.1 |
| INDUSTRY | mill. NOK | 2.1 | 2.1 | | | 1.4 | 0.67 | 0.7 |
| FISHERY | mill. NOK | 1.5 | 1.5 | | | 1.3 | 0.2 | 0.2 |
| Total willingness to pay | | | | 0.31 | 0.06 | | 10.27 | 25.0 |

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# SESSION V DETECTION, TRACKING AND REMOTE SENSING

## OIL SPILL DETECTION UNDER ICE - STATUS REPORT

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### INTRODUCTION

One of the objectives of the United States Coast Guard's Arctic Pollution Response Program is to develop methods to detect, monitor and rapidly determine the extent of oil spilled in the arctic and sub-arctic regions of Alaska.

In the stages following a spill and during cleanup, it is clearly necessary to be able to locate and track the oil. This is especially important if the oil is trapped under a solid ice cover. Tracking may be done in ice-covered waters by using acceptable ice tracking methods; however, in order to locate oil under or in a specific floe, it would be necessary to use a small-scale, highly mobile detection method. If a means of rapidly localizing an under-ice oil spill can be developed, then appropriate recovery techniques that capitalize on that information can be considered.

The Environmental Protection Service of Environment Canada funded a study addressing the following sensing modes to determine the feasibility of their application to the detection of oil in and under ice: radio frequency, acoustic, optical, nuclear and gas sniffer modes. In the early stages of the study, Gill (1979) determined that little work had been published concerning the use of these five selected modes for detecting oil in or under ice. The report concluded that, from an instrumentation feasibility point of view, acoustic or radio frequency techniques would appear to be most preferable. However, each required more study before applications could be categorically determined.

### ELECTROMAGNETIC DETECTION OF OIL UNDER ICE

#### Background

Prior to Gill's study, the most significant work on electromagnetic detection being undertaken at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) involved determining the thickness and electromagnetic properties of sea ice using an impulse radar sounding system operating both on the ice and from a helicopter. First results, while being performed under rather ideal conditions in terms of ice undersurface relief characteristics, were somewhat encouraging; further work was therefore planned (Kovacs and Morey, 1980). Gill concluded that radio frequency radiation, while being able to penetrate reasonable depths of ice, is highly attenuated in first-year ice and less so in multi-year ice at frequencies which would give the desired resolution of an entrapped oil layer. However, if a clear ice/oil boundary is present (i.e., no oil has migrated into brine channels), it should be possible, at least theoretically, to detect the presence of a layer of oil that is not very much thinner than the wavelength being used. This is because the dielectric constant at an ice/water boundary godes from lower to higher values, whereas at an ice/oil boundary it goes from higher to lower values. Hence, the reflection in each situation would be 180° out of phase and easily detected in the return signal. This phase difference would produce a characteristic signature in the radar return, indicating the presence of the oil.

Based on this information, Worsfold et al. (1980) developed a program to test the impulse radar sensing method. This laboratory test program, as outlined by Stapleton et al. (1981), was carried out to check the ability of this sensor to detect oil under ice.

The impulse radar system did not work in the laboratory because the ice that was grown in the flume (0.4 m) was not thick enough for the impulse radar to resolve the top and bottom ice surfaces. The report concluded that the minimum resolvable ice thickness appears to be 0.5 to 0.8 m (over the limit of ice growth in this laboratory) and recommended further testing be carried out in the field or in a lab environment that can grow ice beyond 0.8 m.

During the winter of 1980, the Centre for Cold Ocean Resources Engineering (C-CORE) tested a GSSI 400 MHz impulse radar system as part of the Dome experimental oil spill in McKinley Bay (Goobie et al., 1981). The ice was grown to 1.75 m, with an oil lens at 0.6 m in one section and gas and oil pockets underneath another section. This study concluded that an oil lens with a thickness smaller than the radar pulse wavelength can be detected in sea ice. Similarly, gas or oil pockets on the ice bottom appear to create a distinctive reflective anomaly. The study further concluded that a signal processing and interpretation capability would require a significant development effort before positive identification of oil could be achieved for a range of ice conditions.

### Resonance Scattering Theory

In 1981, the USCG contracted the U.S. Naval Surface Weapons Center to assess the applicability of the resonance scattering theory (RST) in the electromagnetic detection of oil under ice. The results of this study were first presented at the 1982 AMOP Seminar (Jackins et al., 1982).

Specifically, the study focused on the detection and possible material characterization of thin petroleum (oil) layers lying beneath a relatively thick overlayer of ice using radar echoes. The situation, shown in Figure 1, consists of a bilaminar system of two ideally bonded, interacting layers (ice and oil) separating an upper (air) and lower (water) medium; electromagnetic (radar) waves are incident on the bilaminar system from the upper (air) side.

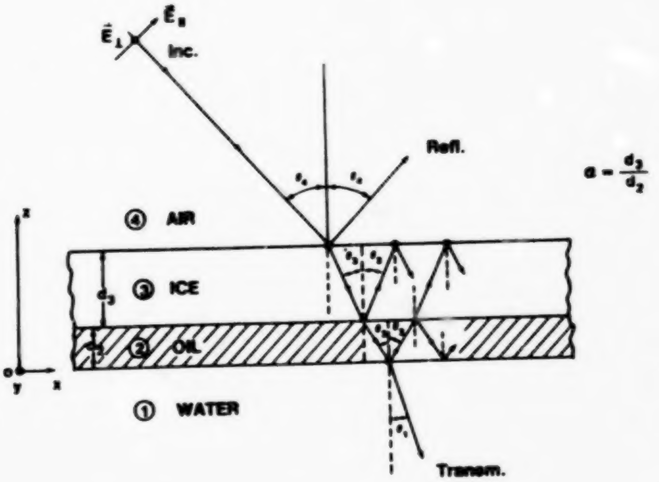

FIGURE 1 THE GEOMETRY

First, a classical model of the system was derived using Maxwell's equations for electromagnetic propagation, leading to expressions for the square of the magnitude of the reflection coefficient, $|R|^2$, for both the bilaminar system and a single layer (ice only) system. Response surface plots, consisting of plots of $|R|^2$ versus both frequency thickness ($f \cdot d_3$) and incidence angle ($\theta_4$), were then generated for various values of $\alpha = d_3/d_2$. These plots clearly showed a change in the shape of the response surfaces for the bilaminar system (particularly for lower values of $\alpha$), as compared to the response surface for a single layer. For a cross-section of the response surfaces at a fixed value of $\theta$, the presence of the oil layer is manifested by a modulation of the resonance (minimum) values of $|R|^2$ vs $f \cdot d_3$, as compared to the single layer system (see Figure 2). Here the classical model values of $|R|^2$ are plotted as the solid lines. The modulation effort becomes more distinct as $\alpha$ decreases.

Jackins and Gaunaurd then constructed an RST model of the same system and demonstrated it to be simpler than the classical model and to accurately predict the magnitude of the reflection coefficient $|R|^2$ in the vicinity of the resonance values of $f \cdot d_3$, the primary region of interest. The RST predictions are shown in Figure 2 with dashed lines. Jackins and Gaunaurd then solved the inverse scattering problem, showing that the dielectric constants and thicknesses of both the oil and ice layers can be analytically determined using radar return information as displayed in Figure 2 (namely, the magnitude of the reflection coefficient ($|R|^2$), the location of the resonance minima (X), and the width of the resonances ($\Gamma$), for the bilaminar and single layer systems). Accordingly, a theoretically promising electromagnetic method exists for both detecting the presence and determining the volume of oil trapped under the ice sheet.

### Discussion

Unfortunately, although the theory is promising, several constraints prevent the direct application of RST to the oil-under-ice problem using currently available radar equipment. First of all, acquisition of the key parameters shown in Figure 2 requires a variable frequency radar. Most currently developed ice profiling radar systems are short pulse, single center-frequency impulse radar systems where the frequency is fixed by the geometry of the antenna. Secondly, the RST model assumes that the bilaminar system is ideally bonded (i.e., a well-defined interface between layers) and that $\alpha$ is sufficiently large to delineate the presence of the oil layer. In fact, in the real world case, the oil/ice interface may be obscured by the presence of oil in the skeletal layer, and the oil layer (which has an equilibrium thickness under flat ice of only 1 cm) may be undetectable due to a large value of $\alpha$. Finally, electromagnetic probing of the bilaminar system will be subject to the same constraints as single layer (ice thickness) profiling. These include high signal attenuation in

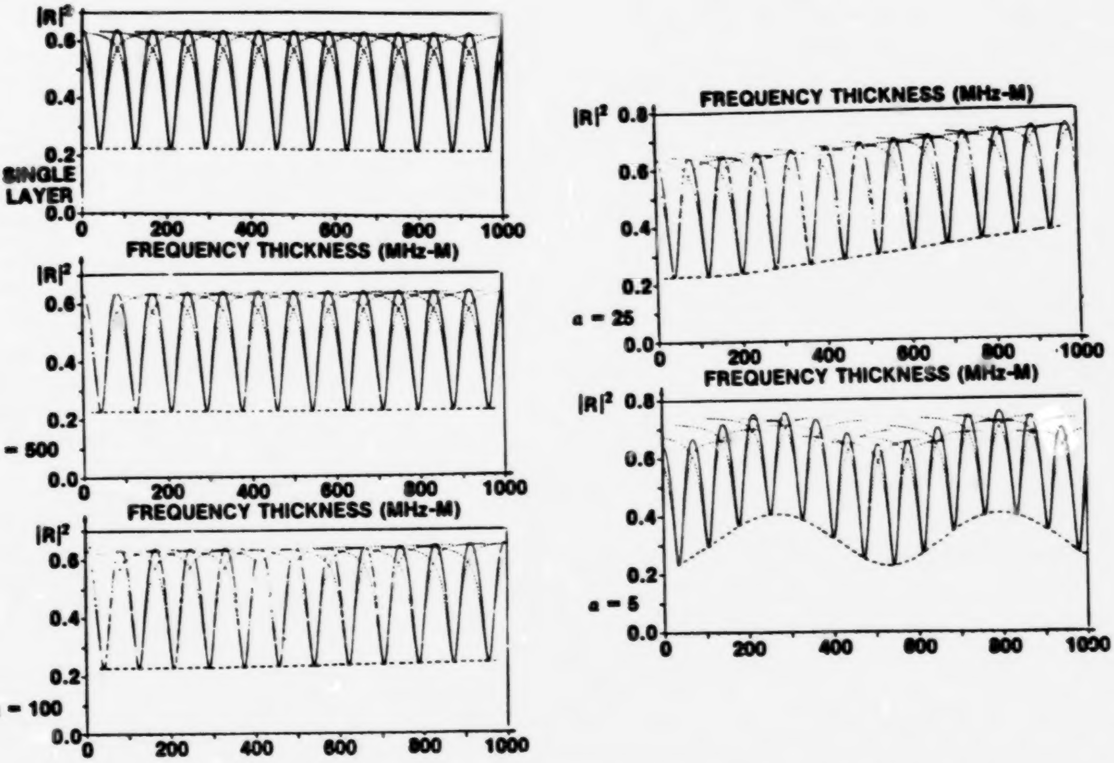

FIGURE 2 RESPONSE CURVES FOR SINGLE AND BILAMINAR CONFIGURATIONS. SOLID LINE FOR CLASSICAL THEORY, DASHED LINE FOR RST.

saline ice, signal scattering from rough ice surfaces (particularly in airborne profiling), and a constant trade-off between ice depth penetration (requiring low frequencies) and oil layer resolution (requiring higher frequencies).

## ACOUSTIC DETECTION OF OIL UNDER ICE

### Background

In his 1979 study, Gill concluded that with regard to acoustic techniques, soundwaves penetrate reasonable ice thicknesses at wavelengths which are closely related to the oil thickness in question. The similar acoustic properties of water and oil (especially heavy oils), however, may cause difficulties in distinguishing between the two; further study is required to establish feasibility.

Based on this information, Worsfold et al. (1980) developed a program to test the most promising sensors (impulse radar and acoustic). A program, as outlined by Stapleton et al. (1981), was then carried out to check the ability of these sensors to detect oil under ice.

The ultrasonic sensor consisted of a sensor head that had to be coupled to the ice surface. Oil was detected under ice within undefined limits of salinity, ice thickness and associated combinations. Further work was suggested to accurately define the salinity/thickness/attenuation parameters. Once these have been determined, the next step would be to establish the transmitted power required through the transducer and the variation of transducer frequency. The actual results were that: a) in 0.3 m of freshwater ice, the necessary signal resolution was available to detect an oil film on the order of a few millimetres; b) in 4°/oo salinity, good signal resolution was achieved in the laboratory but not in the field tests; c) in 7-10°/oo salinity, an ice/water interface could not be detected.

Jones and Kwan (1982) stated that since the density and velocity of sound for oil are very similar to those for water, simple reflection measurements are not likely to give a clear indication of the liquid next to the ice. They performed exploratory work on interfacial effects which might more clearly indicate the presence or absence of an oil layer. They used a 100 kHz sensor (regarded as realistic in terms of the absorption effects and yet with sufficiently small wavelength for other factors to be reasonably well satisfied) on top of freshwater ice. They concluded that there is a reasonable possibility of detecting an oil layer under sea ice; further experimental work is in progress.

To date, most studies on acoustic sensors have placed the tranducers on top of the ice. In April 1981, the USCG contracted the Applied Physics Laboratory of the University of Washington (Prof. R.E. Francois) to look at acoustic detection using a different approach. The objective of this project was to assess the feasibility of using an acoustic system below the water/ice interface as a means of rapidly localizing an under-ice oil spill whose general position is known. Because the transducer is placed below the ice level, the system would have to be used before the oil became encapsulated by the sea ice. The time period for encapsulation to occur depends upon the ice thickness, air temperature, and oil pool thickness. In the NORCO (1975) tests, this time ranged from about 5 days in the fall to 10 days in the spring. The time for localizing and recovering the oil before it is encapsulated is therefore short.

Oil and emulsions pooling under ice tend to form a level surface at the water/oil interface. Such interfaces backscatter acoustic energy very poorly at shallow grazing angles. The possibility of exploiting this characteristic for locating under-ice oil pools depends on there being significant acoustic backscatter from the sea ice around the oil pool, in order to define its boundaries.

The acoustic system discussed here, with its transducer below the ice/water interface, would transmit and directionally receive pulses in such a way as to create a plan view map of the local area. This map would show no signal (darkness) in regions of no reflective return, presumably the oil pool, while regions of signal return (brightness) would indicate regions of sea ice backscatter and no oil. The question is then, how strong is the acoustic backscatter from the ice/water interface?

Because sea ice is a very inhomogeneous material, composed of platelets interspersed with entrapped brine, the properties of the skeletal layer and adjacent sea ice crystal structure were expected to provide significant acoustic backscattering properties, particularly at shorter sonic wavelengths.

### Applicable Surface Backscattering Equations

The amount of acoustic backscatter energy that can be observed from a surface depends on the roughness of the surface and the ensonified area involved. In underwater acoustics, backscatter theory has been extensively treated and need not be repeated here. The parameter in acoustics which defines the intrinsic backscatter property is called the surface backscattering strength. It is determined from experimental measurements and is found to depend upon several variables, such as grazing angle and acoustic wavelength. The value of this term is experimentally determined from measurements and known experimental conditions, using the equations below. We use the notation of Urick (1975).

For nearly horizontal transmission of sound, the reverberation level, RL, from a horizontal surface is given by:

$$RL = SL - 40 \log r - 2\alpha r + Ss + 10 \log A \tag{1}$$

where SL is the source level of the acoustic projector, dB/μPa @ 1 m

$r$ is the range, m

$\alpha$ is the absorption coefficient, dB/m

Ss is the surface scattering strength, defined as

$$Ss = 10 \log I_{scat}/I_{incd}, \text{ dB}$$

where A is the area involved in the scattering process, $m^2$

For our system, we can express the area as

$$A = r\Phi c\tau/2 \tag{2}$$

where $c$ is the velocity of sound in the water medium, m/s

$\tau$ is the pulse length, s

$\Phi$ is the equivalent ideal beam angle (radians) for uniform two-way response

(Urick gives transformation equations from measured beam parameters to $10 \log \Phi$.)

Substitute in Equation 2:

$$10 \log A = 10 \log r + 10 \log \Phi + 10 \log c\tau/2 \qquad (3)$$

so that Equation 1 can be written as

$$RL = SL - 30 \log r - 2\alpha r + Ss + 10 \log \Phi + 10 \log c\tau/2 \qquad (4)$$

Solve Equation 4 for Ss

$$Ss = RL - SL + 30 \log r + 2\alpha r - 10 \log \Phi - 10 \log c\tau/2 \qquad (5)$$

**Experimentation**

In order to determine the surface scattering strength, measurements in the laboratory and field were made over a range of variables (frequency and grazing angle).

A transducer was designed and constructed to cover the frequency range of 60 to 600 kHz and to provide good side lobe suppression. The experimental geometry in the laboratory and general purpose equipment limitations allowed coverage of the 100 to 300 kHz range under all test conditions.

The transducer (Figure 3) consisted of a 3.25 inch (21 cm$^2$) square ceramic plate that was cut to form a 22 x 22 element array. These elements are electrically connected starting with a 4 x 4 array in the center so that additional configurations of 6 x 6, 8 x 8, .... 22 x 22 could be obtained, and different weighting of elements (shading) could be used to suppress side lobes as needed. The assembled transducer, potted in polyurethane, is shown in Figure 4 mounted on a test fixture. A transducer pattern at 200 kHz is shown in Figure 5. The side lobe suppression is better than 30 dB. The transducer beam width as a function of frequency is plotted in Figure 6.

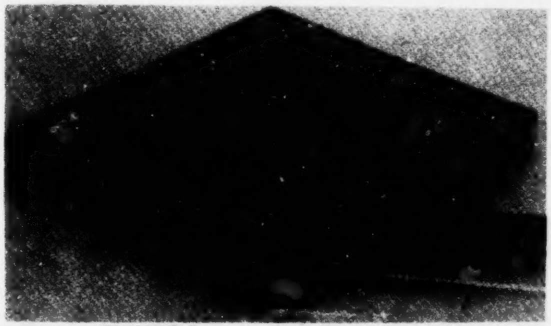

FIGURE 3 THE TRANSDUCER

FIGURE 4 THE ASSEMBLED TRANSDUCER

In the laboratory, testing took place in a temperature-controlled cold room. An insulated tank (Figure 7) limited heat transfer out of the tank to the ice-covered surface area. The transducer was mounted on a circular beam segment which was positioned so that the center of the acoustic beam intercepted the ice-water interface at the same point, regardless of grazing angle. A photograph of the tank in the cold room is shown in Figure 8. The entrance hole was sawed through the ice after freezing the ice to desired thickness.

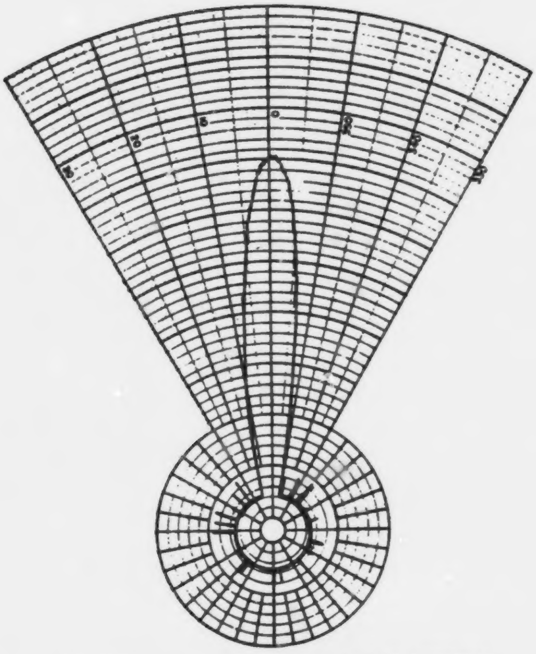

FIGURE 5 TRANSDUCER PATTERN AT 200 kHz

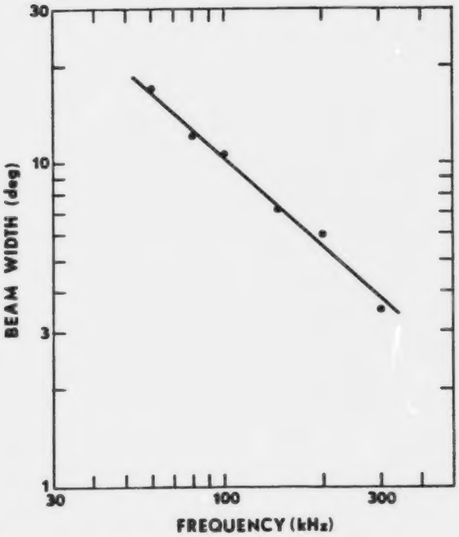

FIGURE 6 TRANSDUCER BEAM WIDTH VERSUS FREQUENCY

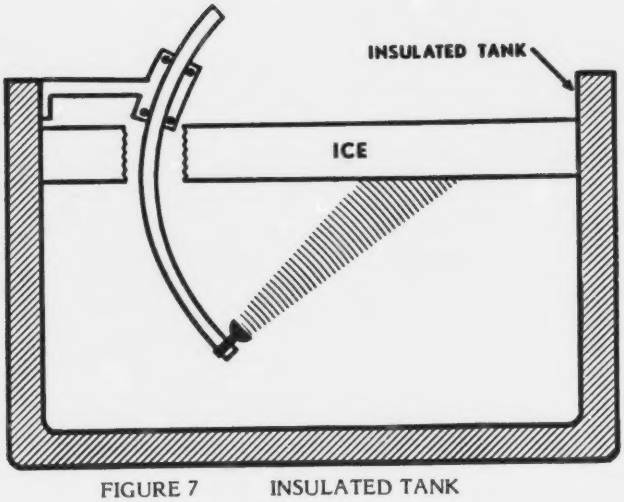

FIGURE 7 INSULATED TANK

FIGURE 8 COLD ROOM

The ice was frozen at different rates to simulate freezing rates that would be experienced in different arctic seasons. The surface scattering strength was determined at each condition. The measurement was also repeated on an Arctic field trip to the Beaufort Sea in October-November of 1982. The same transducer was used, but this time the transducer angle was adjusted with a parallelogram linkage. The transducer was 3 m below water level under ice 60 cm thick. The area for computing scattering strength was substantially larger than that in the laboratory test. Measurements were made in two directions, differing by about 60° in azimuth. The computed scattering strengths of the natural ice differed little from the laboratory ice, which had been grown from artificial seawater of salinity equivalent to typical Arctic seawater (32°/oo).

The experimental data were analyzed and an equation for the surface scattering strength was obtained:

$$Ss = -70 + 24 \log f + 14 \log \sin \theta \qquad (6)$$

where $\theta$ is the grazing angle

f is the frequency, $kH_Z$

The standard deviation of all the data about the regression line defined by Equation 6 was 5.2 dB. In optics, it has been found that "Lambert Law" dependence is a good descriptor of the surface scattering strength of many rough surfaces, insofar as angular dependence is concerned. For Lambert scattering, the angular dependence would be 20 log sin $\theta$ in comparison with our 14 log sin $\theta$ for ice. The means of all data taken at 10, 15, 20, 30 and 45° are shown in Figure 9, along with the corresponding Equation 6 solution. It is clear that our equation is a very good descriptor of the data.

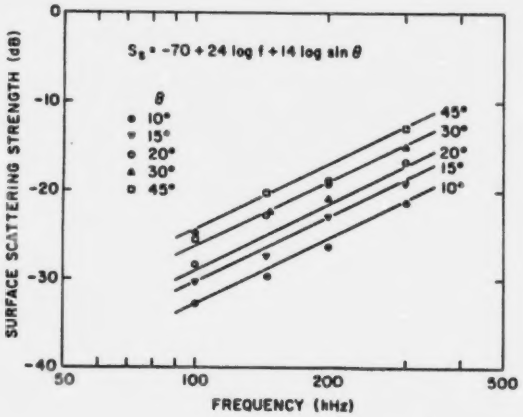

FIGURE 9 SURFACE SIGNAL STRENGTH WITH INCIDENT ANGLE AND FREQUENCY

Measurements were also made with crude oil introduced under the ice layer in the laboratory tank. At shallow grazing angles, no backscatter signal was discernible from the oil. As the grazing angle was increased and the critical angle exceeded, the oil became essentially acoustically transparent and the observed backscatter was related to the ice texture at the oil-ice interface. Our oil sample of Prudhoe Bay crude, provided by the ARCO refinery, Ferndale, Washington, had a sound velocity (at seawater freezing temperatures) about 4-5% greater than the seawater. This indicates a critical grazing angle of about 15°. Below this angle, the acoustic energy incident on an oil surface would theoretically be fully-forward reflected; no energy would enter the oil layer and hence there would be no backscatter from either ice or oil. This was experimentally observed as noted above.

### Results and Discussion

In a laboratory experiment, it is very difficult to obtain measurements at shallow grazing angles that would be observed in actual field operations. Hence, it is very important to obtain a relationship of the ice scattering strength as a function of angle that allows realistic extrapolation into regions where no experimental data were obtained.

The question to be answered now is - Is the ice scattering strength large enough to yield adequate survey ranges? A sample computation can be made using the form of the equation presented earlier and general noise theory (Urick, 1975). The characteristics of a candidate acoustic system are summarized below:

| | |
|---|---|
| Operating frequency | 200 kHz |
| Acoustic absorption | 0.0387 dB/m |
| Transducer diameter (circular piston) | 7.2 cm |
| Beam width (-3 dB down points) | 6° |
| Directivity index | 30 dB |

| | |
|---|---|
| Power | 13.2 watts |
| Efficiency | 50% |
| Source level | 212.6 dB/μPa @ 1 m |
| Receiving sensitivity | -190 dBV/μPa |
| Noise limit - electronic | 6 nV/ Hz |
| Receiving bandwidth | 20 kHz |
| Pulse length | 100 μS |
| Recognition differential | 10 dB |

For the specified problem parameters, Equation 7 yields the effective range at which the specified recognition differential over noise can be maintained:

$$SL + 24 \log f + 14 \log D + 10 \log \Phi + 10 \log c\tau/2 - N - RD = 44 \log r + 2\alpha r \qquad (7)$$

Assuming a transducer depth of 3 m for the specified confidence levels of obtaining a 10 dB recognition differential over noise, the indicated ranges are: 50%, 146.5 m; 84%, 122.8 m; 97.75%, 101.8 m. These are quite respectable distances. Within the above ranges, the ice should show up well. The signal return from the oil is very small at any grazing angle. However, sound may be refracted into the oil layer and backscattered off the ice and back through the oil under some special conditions; this can generally be avoided by minimizing the grazing angle.

In general, the design of an operational survey system would be relatively straightforward, once the system parameters are defined. The type of display system selected will influence beam pattern design, as will ice hole size constraints. A very narrow horizontal beam seems desirable. The selection of operating frequency is very much related to these factors. Parametric studies have not been made and would be the next step prior to constructing such a system. The required resolution, range, and display trade-offs have yet to be made, but the necessary acoustic design information has been obtained.

## SUMMARY

Various studies have concluded that the most likely successful methods for detecting oil under a solid ice sheet would be those using either electromagnetic or acoustic sensors. The United States Coast Guard funded a study on each of these methods, the results of which were presented in this paper.

The first study was conducted by the Naval Surface Weapons Center; they developed the resonance scattering theory (RST) prediction for the reflection coefficient of a bilaminar plane configuration of dielectric layers (ice and oil) separating two dissimilar, nonconducting media (air and water). This prediction was compared to the classical model prediction; the RST was shown to be simpler and more accurate. Using the locations, widths and amplitudes of the resonances (from the radar return information), we can determine the thickness and dielectric compositions of the interacting layers (ice and oil). This process disentangles which set of resonance features in the reflected echo is caused by which of the layers. Unfortunately, although the theory is promising, there are several constraints preventing the direct application of RST to the oil-under-ice problem using currently available radar equipment. However, based on the results of this study, ESSO Canada and EPS are doing further research, the results of which are presented elsewhere in these proceedings.

The second U.S. Coast Guard study was conducted by the Applied Physics Laboratory of the University of Washington, where the application of acoustic methods to the localization of under-ice oil spills using an under-ice transducer was studied. An experimental investigation was conducted to determine the acoustic backscatter characteristics of sea ice in comparison to that of oil pooled under ice. The surface backscattering strength of level sea ice was determined as a function of frequency and grazing angle. The results indicate that an under-ice sonar could effectively map spilled oil under ice in an area several hundred metres in diameter in one setup. Now that the necessary acoustic design information has been obtained, the next step is to undertake a parametric study to determine the required resolution, range and display trade-offs.

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# A MICROPROCESSOR-CONTROLLED SAMPLER FOR *IN SITU* EXTRACTION OF HYDROCARBONS FROM WATER

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## INTRODUCTION

The technology for collecting and storing water samples for analysis for pesticides, hydrocarbons and toxic heavy metals has not advanced significantly over the last two decades. Present sampling techniques involve collecting a large volume of water and storing it for shipment to a laboratory for extraction and analysis. This paper describes a new device for water sampling based on the principle of extracting the water *in situ* rather than collecting it. This method of sampling has many advantages, including convenience in sample storage and shipment, and a greatly reduced possibility of sample contamination.

Several research groups have realized the advantages of switching to a method of sampling that extracts the contaminants from water *in situ* using solvents (Ahnoff and Josefsson, 1974), XAD resins (Osterroht, 1974; Dawson et al., 1976), mixed bed columns (Scura and McClure, 1975), polyurethane foam (de Lappe et al., 1979), and other methods. All of these devices have remained at the research stage because they are cumbersome, inefficiently designed, and expensive to produce.

The sampler described here is intended for widespread use by monitoring agencies that have limited experience in water sampling and analysis. It relies upon a microprocessor controller to achieve an almost unlimited degree of flexibility in sampling. The details of the sampler design and some results that have been obtained in laboratory and field testing are presented in the following sections.

## SAMPLER DESIGN

The sampler consists of four main components: an extraction column containing polyurethane foam, a pump, a flow meter, and a microprocessor controller. The controller allows the selection of three different pumping speeds (pulsed, 75 mL/min, and 150 mL/min), and twelve different pumping regimes. The pumping regimes allow the choice of length of pumping time, and also allow for interrupted pumping so that the sampler turns on for a set period every few hours. This latter arrangement is useful if the sampler is moored for a period of time doing long-term water quality monitoring.

A photograph of the sampler is shown in Figure 1. A Teflon intake tube, which extends away from the sampler, brings the water into the extraction column (a Teflon tube containing suitably cleaned polyurethane foam). At the inlet end of the extraction column, an optional filter assembly removes particulate matter from the water, thus allowing differentiation between dissolved and particulate material. The outlet from the sampling column leads into a 0-24 V magnetically-coupled two-gear micropump mounted inside the unit. Flow through the pump is measured by a microflow sensor which in turn empties into the discharge tube directed to the side opposite the intake.

All components are located within the anodized aluminum housing, with the exception of the extraction column which is exterior and removable. Switches for setting the desired flow rate, pump time, and delay are mounted on the top of the sampler and use Hall Effect transistors to communicate through the instrument casing to the microprocessor. The microprocessor also monitors the flow rate from the flow sensor, adjusts the pump voltage to give a constant flow, and shuts off the pump should the flow rate decline below a given level. The power supply consists of 18 D-cell batteries and provides 9 volts or 248 ma. It can be expected to power the unit for approximately 120 hours.

Each extraction column is prepared in the laboratory under clean-room conditions and, as a unit with the inlet tube, sealed until attached to the sampler. The column seals are broken only as the tube is mounted, thereby preventing contamination. Once sampling is completed and the unit raised back onto the sampling vessel, the extraction column is removed from the unit, capped with suitably lined screw caps, and transported for analysis.

## COLUMN TESTING

The columns that are used for *in situ* extraction are Teflon tubes filled with polyurethane foam. The use o polyurethane foam as an extractant medium for both heavy metals and organics has been developed over the past 1 years. The attraction of using foamed cellular materials for extraction arises from their favourable hydrodynami properties. High flow rates can easily be achieved through the foam. Polyurethane foam plugs have large availabl surface areas and an excellent capacity for retaining various extracting agents. The foam itself is inexpensive, easy t clean, and is stable and inert in organic solvents, acids, bases and at temperatures less than 200°C. It has been utilize for the concentration of trace metals and organics from dilute solutions both in its uncoated states and with coating specific to the particular application (Moody and Thomas, 1982).

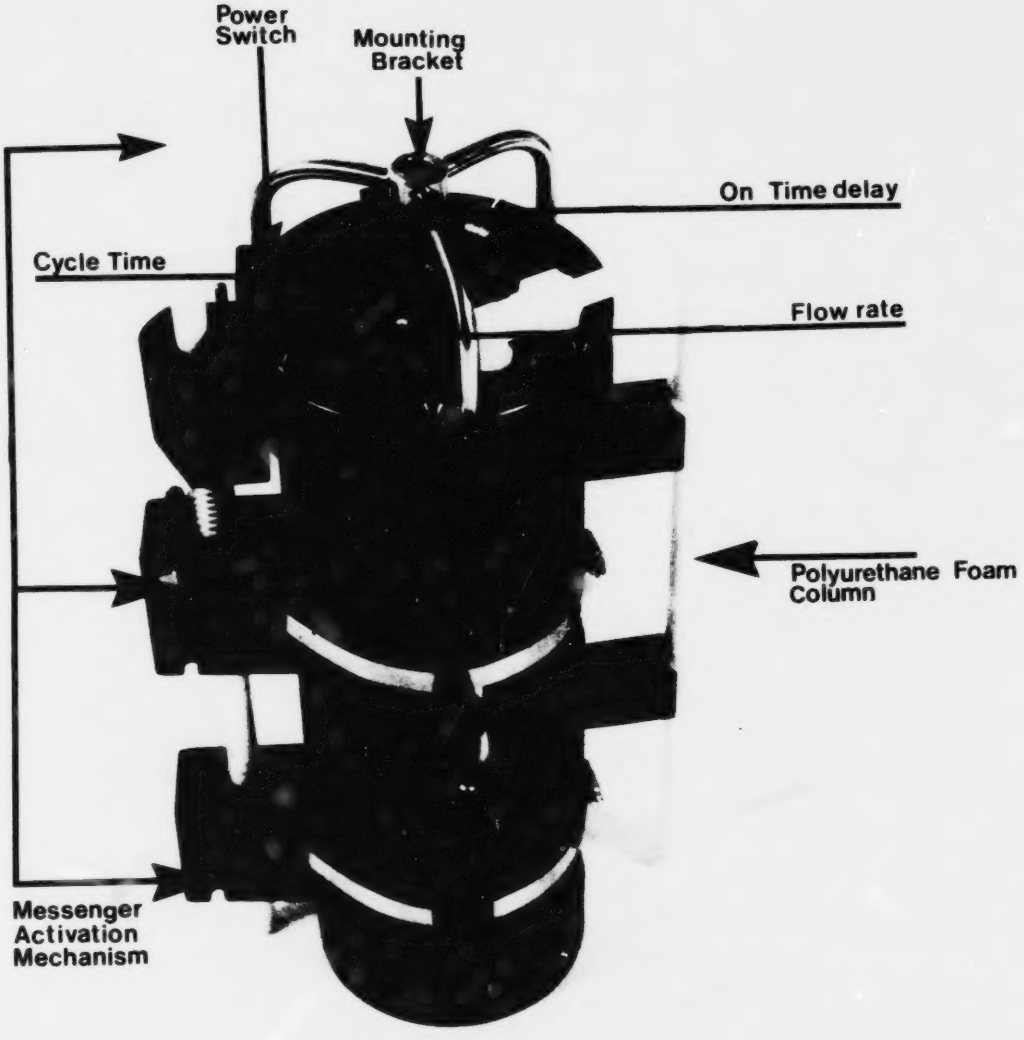


FIGURE 1 THE IN SITU SAMPLER

During the development of this sampler, work has concentrated on testing the extraction capabilities of foam in a column configuration with flow rates of about 100-150 mL/min. Figure 2 shows the particle retention characteristics of the foam; the column can be used in conjunction with a filter if full retention of particulates is required.

Table 1 summarizes extraction efficiency results for the column from an experiment with PAHs dissolved in distilled water. Other experiments with alkanes at low levels and with dispersed oils at high levels are in progress but not ready for publication.

Results from the use of an earlier version of the in situ sampler at the Baffin Island Oil Spill project have given qualitative and quantitative data on hydrocarbons in the water column before and after an experimental oil spill. In this application, a filtration unit was used ahead of the column. Figure 3 shows gas chromatograms of a background sample saturate; aromatic fractions for the analysis of both the filter and polyurethane foam column are included. This should be compared with Figure 4, an in situ sample taken after the experimental oil spill which clearly shows the crude oil dispersed and dissolved in the water column. Figure 5 shows the quantitative measurements made with the in situ sampler before and after the dispersed oil spill. The sampler documented large increases in detectable oil concentrations, decreasing gradually to background levels after about 7 days. In all of the samples, the particulate fraction was dominated by saturates while the "dissolved" fraction of the foam primarily consisted of aromatic hydrocarbons.

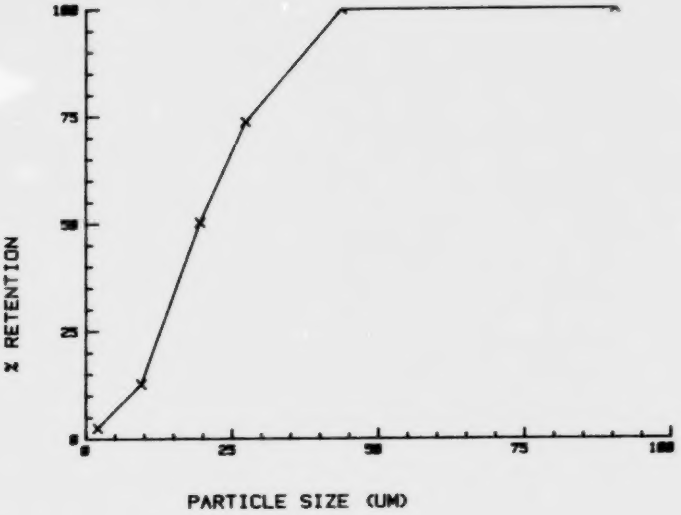


FIGURE 2 PERCENT RETENTION VERSUS PARTICLE SIZE FOR A POLYURETHANE FOAM COLUMN

TABLE 1 POLYURETHANE FOAM COLUMNS: EXTRACTION EFFICIENCIES FOR DISSOLVED PAHs IN DISTILLED WATER

| Compound | Concentration (μg/L) | Total Volume (L) | Extraction Efficiency (%) |
|---|---|---|---|
| Anthracene | 28.9 | 4.7, 6.3, 6.7 | >99.6 ± 0.2 |
| Benz(a)anthracene | 6.5 | 3.4, 5.5, 6.4 | >98.3 ± 0.2 |
| Benzo(a)pyrene | 0.6, 0.75, 1.1 | 11, 15, 15 | >99.3 ± 0.3 |

Notes:

1. Each experiment was performed in triplicate.
2. Solutions were generated by pumping distilled water through NBS generator columns.
3. Flow rates varied from 150-250 mL/min.

## DISCUSSION

In using the earlier version of the *in situ* sampler at the BIOS experiment, the following advantages over traditional "batch" water sampling were noted:

a) ability to extract a large volume of water (40-80 L) conveniently;

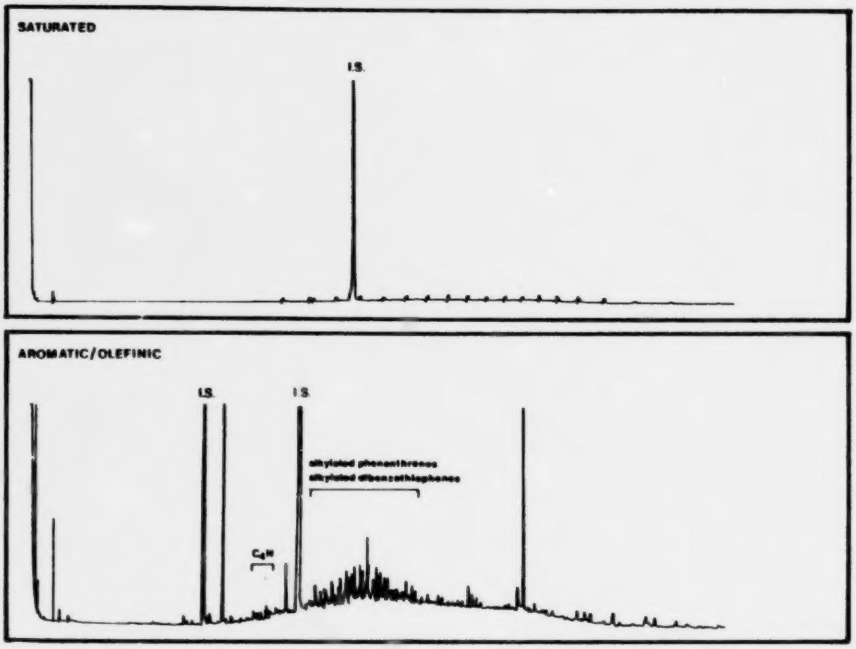
b) ability to obtain integrated samples over an extended time period;

c) ability to distinguish between "dissolved" and particulate hydrocarbons;

d) ease of sample storage and handling under remote, difficult conditions;

e) cleanliness and lack of contamination due to minimal handling steps;

(a) polyurethane foam



(b) filter

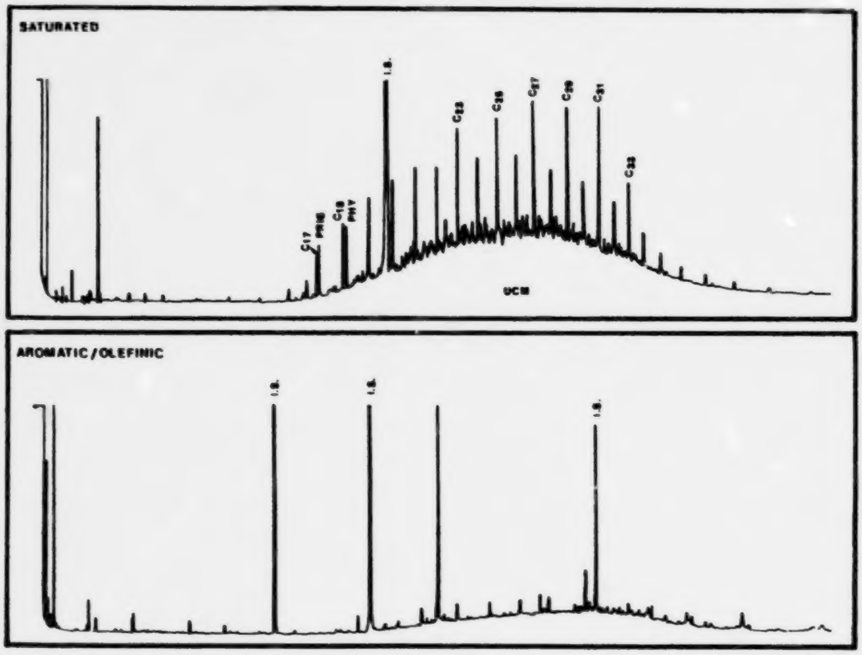
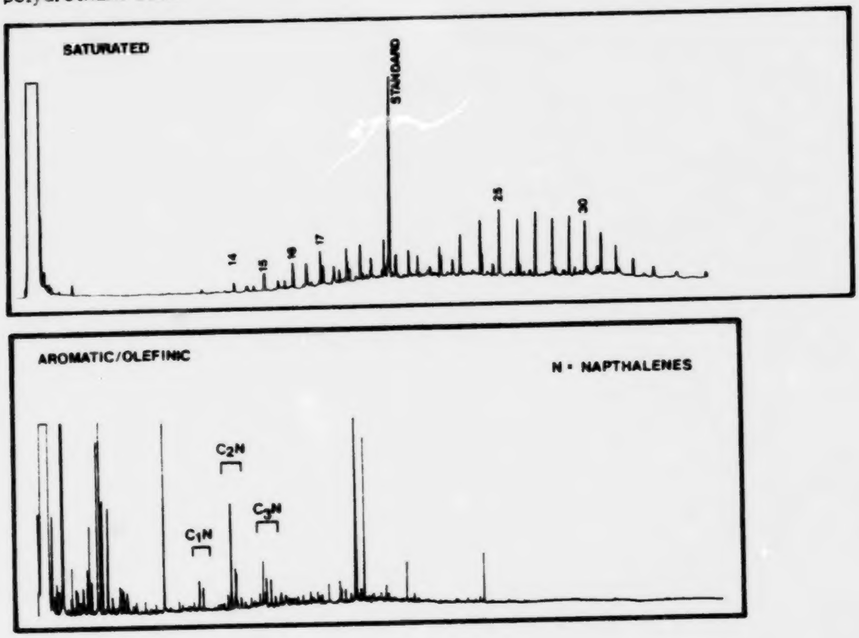


FIGURE 3 GAS CHROMATOGRAMS OF A BACKGROUND WATER SAMPLE FROM RAGGED CHANNEL, BAFFIN ISLAND, N.W.T.

(a) Saturate and aromatic fraction, polyurethane foam
(b) Saturate and aromatic fraction, filter (from Boehm, 1981).

(a) polyurethane foam



(b) filter

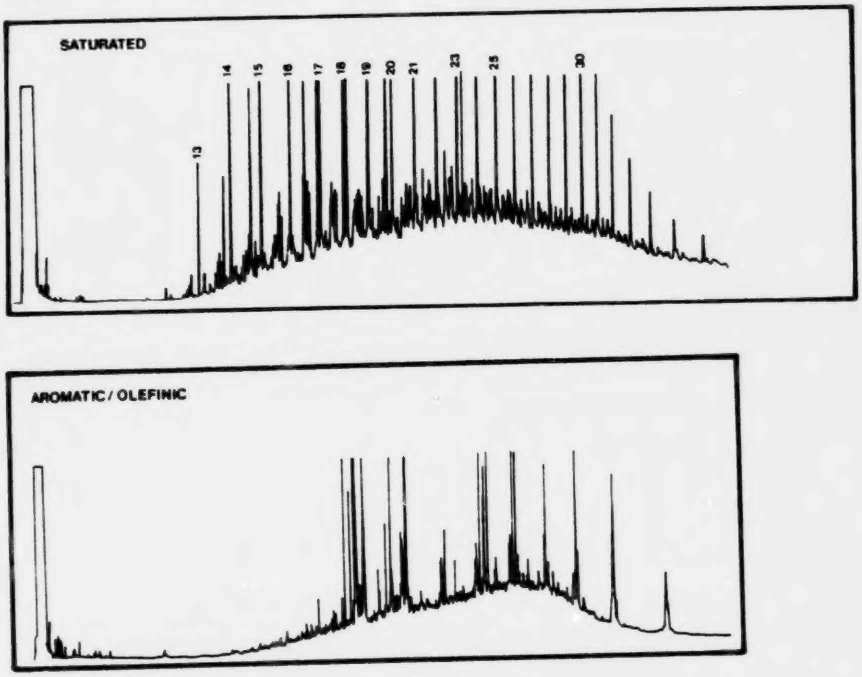


FIGURE 4 GAS CHROMATOGRAMS OF A WATER SAMPLE FROM RAGGED CHANNEL, BAFFIN ISLAND, N.W.T., 2 DAYS AFTER A 15 $m^3$ EXPERIMENTAL OIL SPILL

(a) Saturate and aromatic fraction, polyurethane foam
(b) Saturate and aromatic fraction, filter (from Boehm et al., 1982).

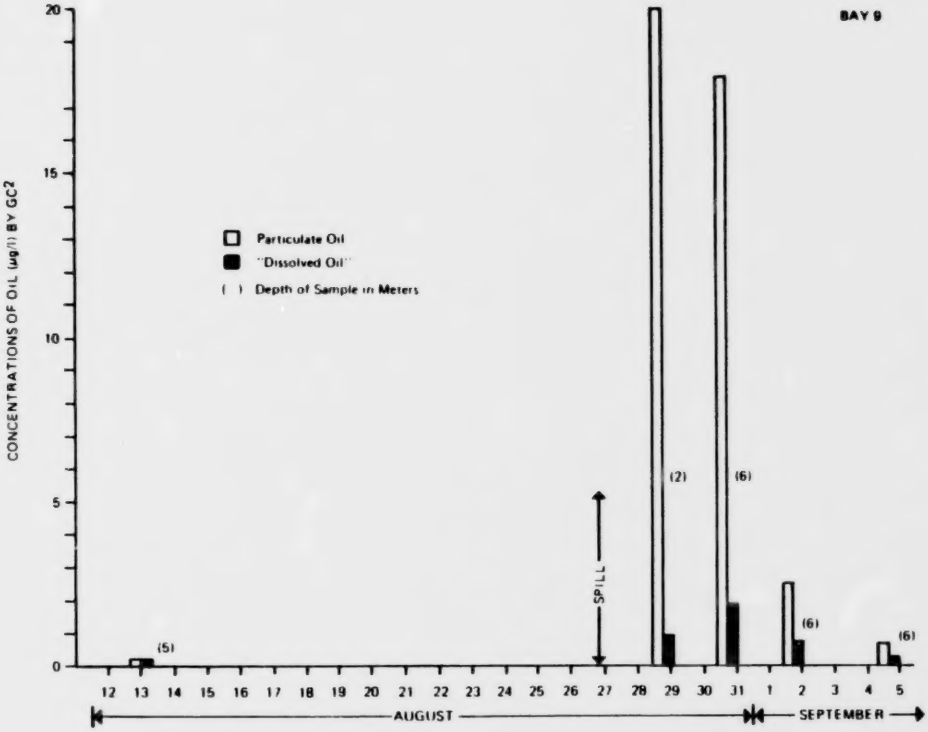


FIGURE 5 CONCENTRATIONS OF HYDROCARBONS IN THE WATER COLUMN AFTER A 15 $m^3$ EXPERIMENTAL OIL SPILL, AS DETERMINED BY ANALYSIS OF WATER SAMPLES TAKEN BY THE IN SITU SAMPLING METHOD (from Boehm et al., 1982)

f) ability to sample cleanly underneath an oil slick.

The following disadvantages were noted during the BIOS experiment with in situ sampling: lack of proof that the columns were completely extracting hydrocarbons from the water; and awkwardness of the sampling equipment. With the new version of the in situ sampler, self-contained and microprocessor-controlled, the problems of awkwardness have been solved. The research to date on the extraction efficiencies of the polyurethane foam indicate that extraction is quantitative for dissolved hydrocarbons. In situ sampling appears to offer an attractive alternative to traditional water sampling methods and should be considered for applications that require time-integrated samples, long-term monitoring, sampling under an oil slick, or large samples for trace analysis.

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# SATELLITE-TRACKED BUOY TRAJECTORIES IN THE BEAUFORT SEA

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## INTRODUCTION

Efforts to predict the movement of oil spilled into the marine environment are often frustrated by a lack of adequate oceanographic data. This is particularly true in the Beaufort Sea (Figure 1), an area of active offshore oil exploration in both Alaskan and Canadian areas, where little is known about the circulation patterns. In addition, the region is ice-covered for much of the year and, even during open water in the summer months, the proximity of the ice edge and floating ice complicate efforts to predict the movement of an oil spill.

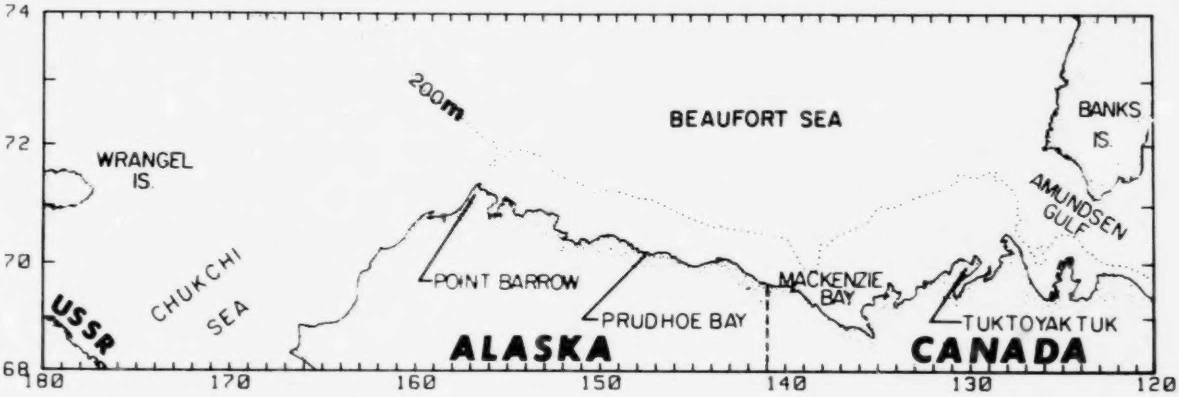

FIGURE 1 AREA OF STUDY

In 1979, as part of its investigation into the fate of potential Arctic oil spills, the U.S. Coast Guard Research and Development Center (R&DC) began a series of drift studies in the Beaufort Sea using satellite-tracked buoys. Since its inception, this research program has been a cooperative effort between R&DC and Canadian Marine Drilling, Ltd. (CANMAR), a subsidiary of Dome Petroleum. Thus far, the study has focused on the drift of satellite-tracked platforms, both free-drifting and platforms placed on sea ice, deployed at the CANMAR drilling sites north of the Tuktoyaktuk Peninsula.

This report describes the results of free-drifting buoy deployments during the summers of 1979 through 1981. It is not the intent to present an exhaustive analysis of the buoy motions but rather to outline the trajectories, with occasional references to their relationship with large-scale atmospheric systems.

Throughout this report, Julian dates (JD) are presented where appropriate because this calendar system, in which the days of the year are numbered sequentially starting 1 January, is convenient when dealing with drift intervals spanning several months.

## MEASUREMENT PROGRAM

### Buoy Tracking System Description

Two different satellite tracking systems and three different hull designs were employed in this study. The first tracking system, used only in 1979, was the Random Access Measurement System (RAMS) on board the NIMBUS 6 satellite; Kirwan et al. (1976) provide a summary of RAMS. The advertised position accuracy of RAMS is ± 5 km. The second tracking system, used after 1979, was the ARGOS system on board the TIROS/NOAA series satellites. It provides a system position accuracy of approximately 300 metres; Bessis (1981) describes the ARGOS system. For both the RAMS and ARGOS systems, the buoy positions are determined by a Doppler shift in the carrier frequency of the buoy transmissions during a satellite pass.

Three different buoy hulls were used. The first type, used in 1979, was designed and constructed at Scripps Institute of Oceanography (SIO) and will be referred to as the SIO hull. It consisted of a fibreglass cylinder approximately 3 m long (Figure 2). The remaining two hull types (Figures 3 and 4) were designed and manufactured at Polar Research Laboratory (PRL) of Santa Barbara, CA. The first was the standard PRL hull (Figure 3) which is approximately the same length as the SIO hull. The PRL hulls used in 1980 were fitted with nylon window shade drogues tethered to the buoy with 30 m of nylon line. A drogue sensor which incorporated a load cell was mounted on the lower end of the buoy hull. This sensor provided a drogue "on/off" indicator along with the position data. This hull type will be referred to as the PRL hull. The final hull type (Figure 4) used in this study was designed by PRL especially for CANMAR. It is 1.12 m in diameter with a 0.20 m drag skirt. The buoy floats nearly awash, with only a 0.38 m antenna above the water surface. It will be referred to as the CANMAR hull.

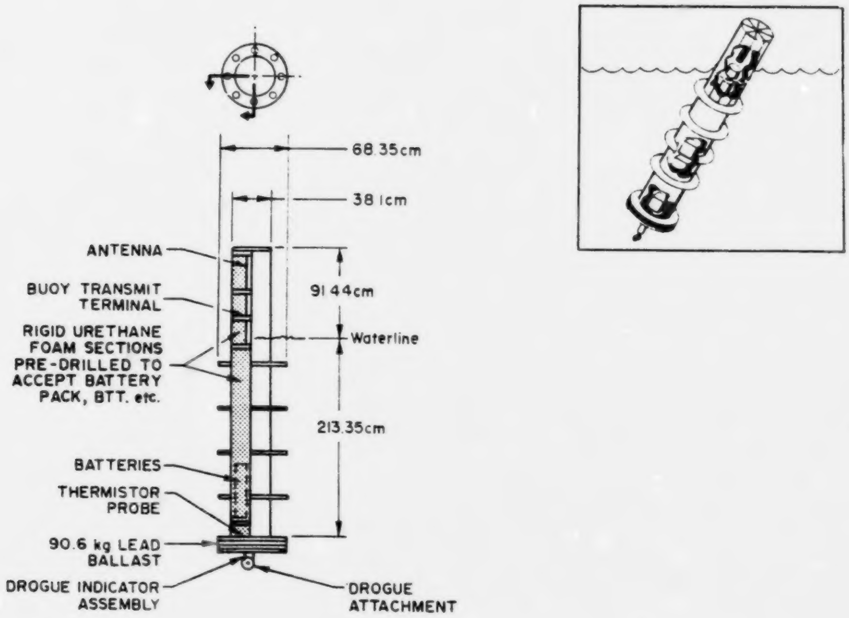

FIGURE 2 SCRIPPS INSTITUTE OF OCEANOGRAPHY (SIO) HULL DESIGN

Even in the case of the drogued PRL buoys, it is probably best to assume that all the drifters followed the currents in the upper (1 to 2 m) portion of the water column. The actual fate of the drogues is uncertain, as is described later. There is, of course, some downwind buoy movement due to the wind stress acting directly on the exposed (above the waterline) portion of the hull. It is variously called leeway or slippage (with respect to the water), and it contaminates the surface current information indicated by the buoy trajectory.

For the SIO and PRL hulls, the ratio of the submerged area to exposed area was at least 2:1; thus, the wind stress on the buoy hull is not expected to dominate the buoy motions. Kirwan et al. (1978) attempted to correct the buoy movement records by eliminating direct wind effects, but found unrealistically high corrections. They therefore concluded that the uncorrected records were better representations of the ocean surface currents. McNally (1981), using drifters with SIO hulls in the northern Pacific, showed that there was no significant systematic difference between the movement of undrogued drifters and those with drogues at 30 metres, which suggests that the slippage of his buoys was small compared to the wind-driven currents.

The hull design of the CANMAR buoys is quite different from that of the relatively similar SIO and PRL hulls. The intent of CANMAR was to develop a buoy hull which would travel like an oil slick. The issue of how well the movement of the CANMAR hull fulfills this goal is not addressed in this report. The drift data are presented; the movement of the CANMAR hull is compared to the PRL hulls for the cases in which the two types were released together.

### Position Data Processing

For the 1979 deployment, the RAMS system provided an average of one good fix every 1.4 days. On some occasions there were four or five good positions per day, while at other times there were data gaps of up to 10 days. The sporadic nature of the data limited the sophistication of the data processing. As a result, a simple, two-point linear

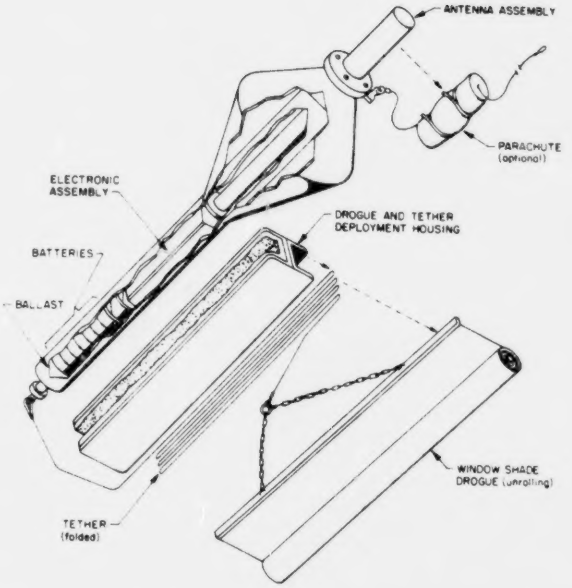

FIGURE 3 POLAR RESEARCH LABORATORY (PRL) HULL DESIGN

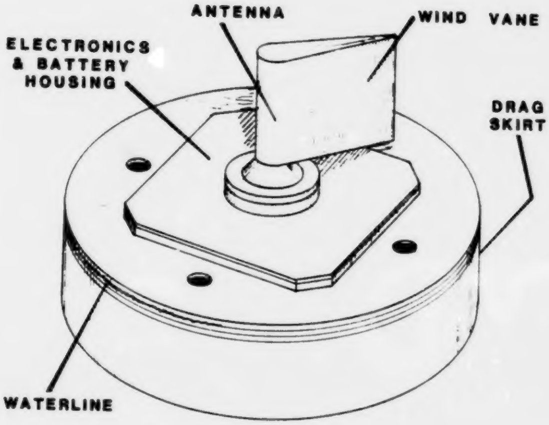

FIGURE 4 CANMAR HULL DESIGN

interpolation scheme was used to generate an equally spaced record of positions with a time interval of 48 hours; no filtering was attempted.

The position data collected from the ARGOS system in 1980-1981 were less sporadic. There were very few data gaps; approximately 10 good fixes were recorded each day for all of the platforms. The position data were processed in a manner following Robe and Maier (1979). Equally spaced position records with a 3-hour time interval were computed using a four-point linear interpolation scheme. These position records were then filtered using a low-pass filter with a cut-off of 1.16 x $10^{-5}$ Hz (one cycle per day). This filter removes the random system errors and most of the tidal effects. The buoy drift speeds and directions were computed from the filtered files using a two-point backward differencing scheme.

### Sea Ice Concentrations

Data concerning sea ice concentrations and distributions in the Beaufort Sea were obtained from atlases prepared by the Joint Ice Center (JIC) in Suitland, Maryland (NOAA/U.S. Navy Joint Ice Center, 1979-1981). The terminology used in the text follows that employed by the JIC. The ice concentrations are presented in tenths. Open water refers to ice concentrations of <1/10, and ice-free indicates that there is no sea ice present. The ice is also classified by age; multi-year and second-year ice are indicated by OLD (2.0 to 3.5 m thick), while first-year ice (FY) includes all first-year ice types (~30 cm to 2 m thick). Young ice (10 to 30 cm) is denoted by YNG, and N refers to new and nilas (an elastic crust of ice <10 cm thick).

### Wind Data

Direct wind measurements over water or ice in the Arctic Ocean are rare. As a result, surface wind data are computed from the distribution of surface atmospheric pressure using the geostrophic equations and applying a relationship between geostrophic wind and the actual surface wind. This method is described by Petterssen (1958).

The data used in this report were obtained from two sources. The first, used only in 1979, was the National Meteorological Center (NMC) 1,000 mb velocity field, a wind field which is essentially geostrophic. The second source, used in 1980 and 1981, was the daily Arctic atmospheric pressure fields presented by Thorndike and Colony (1981) and Thorndike et al. (1982).

## YEARLY BUOY TRAJECTORIES

### 1979

Seven free-drifting buoys, all with SIO hulls and NIMBUS electronics, were deployed into ice-free waters at CANMAR drilling sites north of Richards Island (Figures 5a through 5e). They were released on two dates; three buoys were released on 9 August (JD 221) and four buoys on 30 August (JD 242), along a north-south line 50 km long starting approximately 50 km offshore. None of the buoys had drogues. The goal was to study both the spatial and temporal variability of the nearshore surface flow.

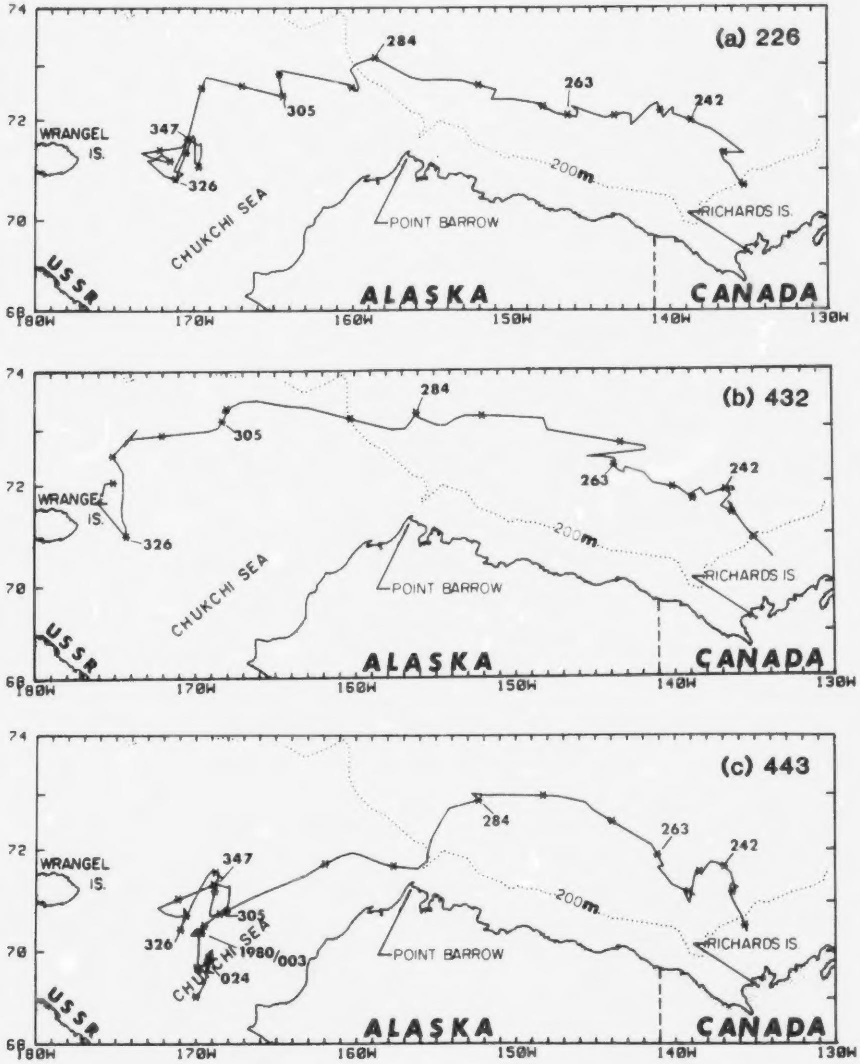
(a) 226
(b) 432
(c) 443
284
263
242
305
347
326
1980/003
024
WRANGEL IS.
CHUKCHI SEA
200m
POINT BARROW
RICHARDS IS.
USSR
ALASKA
CANADA
74
72
70
68
180W
170W
160W
150W
140W
130W

FIGURE 5 TRAJECTORIES FOR BUOYS RELEASED IN 1979: (A) BUOY 226, (B) BUOY 432, (C) BUOY 443, ALL RELEASED 9 AUGUST (JD 221). THE DATES ARE GIVEN IN JULIAN DAYS; ASTERISKS ARE PLOTTED AT 7-DAY INTERVALS

Of the seven buoys released, one stopped transmitting immediately after its release and another grounded on Richards Island a short distance from the release site. The remaining five buoys traversed the Beaufort Sea in an east-to-west direction.

The three buoys released on 9 August (JD 221) moved rapidly to the northwest out of the deployment area (Figure 5a through 5c) under moderate to strong southeast and south winds in mid-August. They continued to move predominantly from east to west across the Beaufort Sea, parallel to the Alaskan coast and approximately 200 km

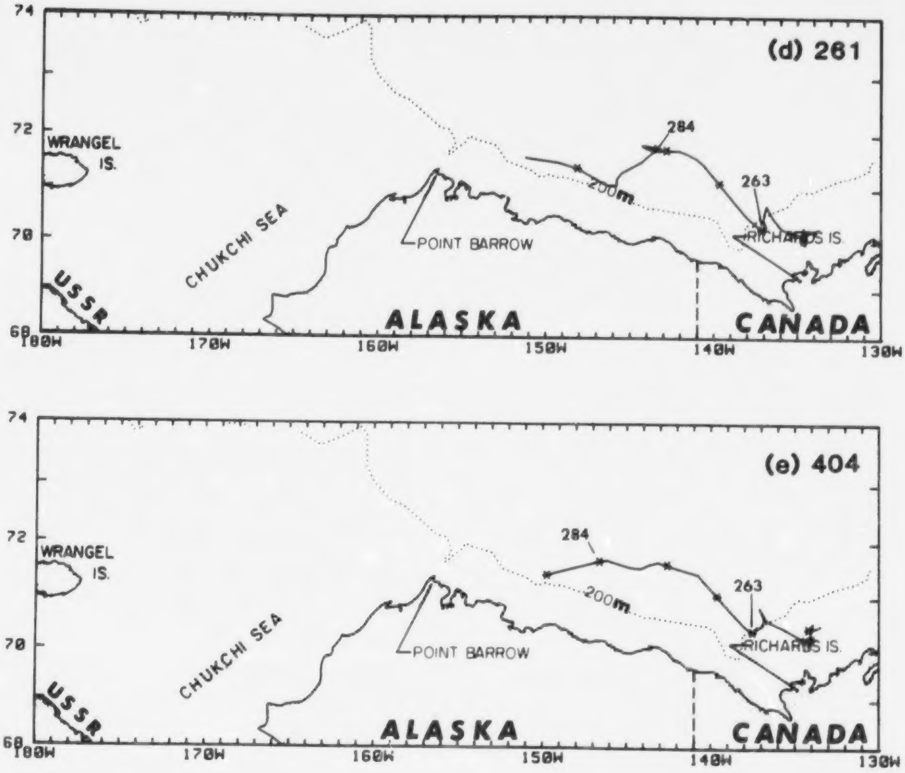

FIGURE 5 TRAJECTORIES FOR BUOYS RELEASED IN 1979 (CONT'D): (D) BUOY 261 AND (E) BUOY 404, BOTH RELEASED 30 AUGUST (JD 242). THE DATES ARE GIVEN IN JULIAN DAYS; ASTERISKS ARE PLOTTED AT 7-DAY INTERVALS

offshore. This movement occurred in ice-free and open water considerably off the continental shelf. They returned to the continental shelf near Pt. Barrow in mid-October, approximately 2 months after their release. To the west of Pt. Barrow, they turned somewhat to the south and entered the Chukchi Sea where they encountered 7/10 to 10/10 N/YNG sea ice in mid-November. By 11 February, 1980 (JD 42), all three of these buoys had ceased transmitting.

The two remaining buoys from the 30 August (JD 242) deployment also moved quickly out of the release area to the northwest, and thence to the west along the Alaskan coast (Figure 5d and 5e). They moved somewhat inshore of the three released earlier, but off the continental shelf as well. Their early movements were in ice-free waters, but by mid-October they encountered 7/10 to 10/10 N/YNG sea ice east of Pt. Barrow and stopped transmitting positions shortly thereafter.

Murphy et al. (1981) compared weekly averaged buoy motions with similarly averaged surface winds calculated from the NMC 1,000 mb atmospheric velocity field. For the period that the buoys moved in either ice-free or open water, they computed the buoy speed as a percentage of the surface wind speed and the deflection angle (the angle that the buoy moves relative to the wind direction). They found considerable scatter in the data at low wind speeds; however, for surface wind speeds greater than 5 m/s, the buoys were found to move consistently at 3.8% and 22° to the right of the local wind.

## 1980

In 1980, eight buoys, tracked using the ARGOS System, were released into ice-free waters at 4-day intervals over the period from 13 August (JD 226) through 2 September (JD 246); the launch site is denoted by an "X" in Figures 6 and 7. Two hull types were used: four PRL hulls with window shade drogues tethered at 30 metres and four undrogued CANMAR hulls. The primary goal of the 1980 effort was to examine the temporal variability of the surface flow in the study area.

Of the eight buoys released, one failed immediately due to an apparent electronic malfunction, and two others provided positions for only a few days. At least one of these was reportedly hit by a vessel operating in the study area. The tracks of four of the five remaining buoys are shown in Figures 6 and 7; the fate of the fifth buoy is discussed later.

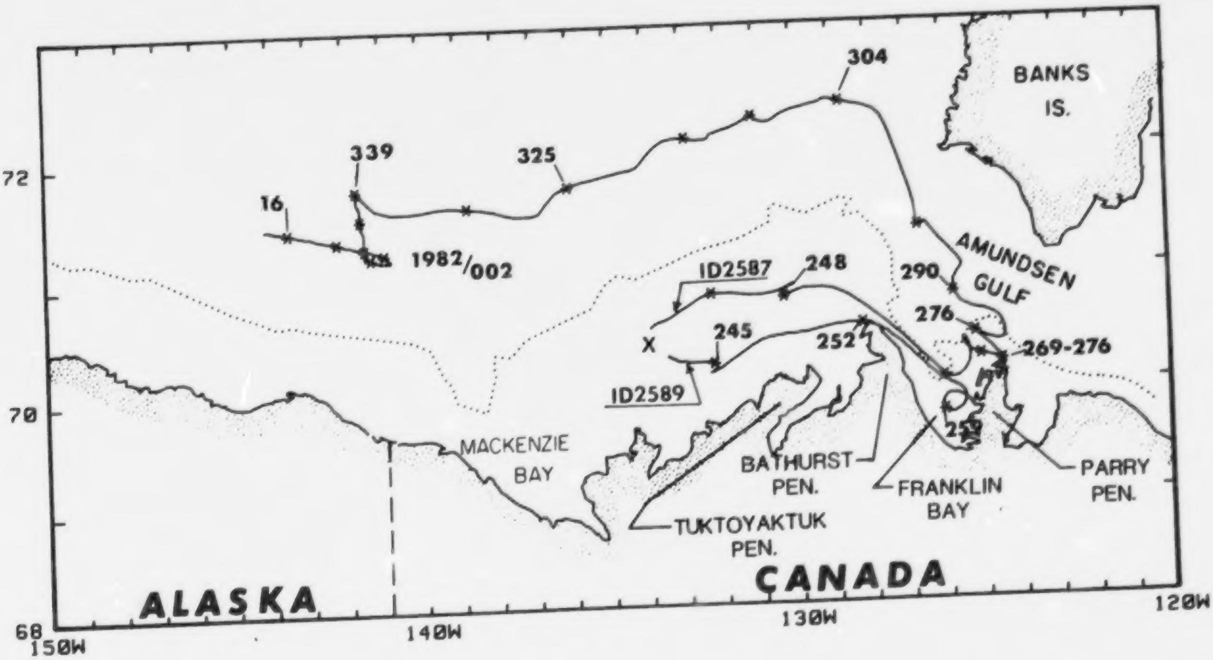

FIGURE 6 FILTERED TRAJECTORIES FOR BUOY 2587 RELEASED 21 AUGUST (JD 234) 1980 AND BUOY 2589 RELEASED 25 AUGUST (JD 238) 1980. THE APPROXIMATE LOCATION OF THE RELEASE SITE IS MARKED BY AN "X". THE DATES ARE GIVEN IN JULIAN DAYS; ASTERISKS ARE PLOTTED AT 7-DAY INTERVALS

The 1980 tracks are considerably different from those in 1979, particularly the easterly motion which occurred in the first few weeks after the releases. During this period (mid-August to mid-September), the atmospheric circulation in the Arctic Ocean was dominated by a low pressure system which resulted in west and northwest winds in the study area. The response of two of the buoys (2587 and 2589), both with CANMAR hulls, was quite dramatic (Figure 6). They moved persistently to the east, entering Amundsen Gulf and then Franklin Bay. Twelve-hour average speeds of up to 0.59 m/s were measured in the area north of Bathurst Peninsula. Both buoys beached on the Parry Peninsula, one permanently (2589, on 17 September, JD 261) and the other (2587) for 2 weeks (21 September, JD 265, to 5 October, JD 279), a period during which there was a considerable amount (8/10 to 10/10) of FY/OLD sea ice in the vicinity.

The trajectories of buoys 2587 and 2589 are consistent with the eastward surface flow for persistent northwest winds observed by MacNeill and Garrett (1975). MacNeill and Garrett also recognized the existence of a vigorous flow down the eastern side of Bathurst Peninsula.

Unfortunately, the early position data from the drogue-equipped PRL hulls must be viewed with skepticism. The drogue tethers (30 metres) were too long for the shallow water which they entered under the forcing of the northwest winds. Often, these buoys were near or within the 50-metre bathymetric contour; therefore, it is likely that the drogue was in contact with the bottom for extended periods. Adding to the uncertainty is the fact that the actual fate of the drogues is unknown because, in all cases, the drogue "on/off" indicator showed that the drogues had detached shortly (<10 days) after deployment.

The drogue problem explains the lack of significant eastward movement of the drogued buoys during the persistent northwest winds. In fact, one of the buoys (2583) was clearly in water too shallow for the drogue and never returned to deep water. Its track is of little value and is not plotted in Figure 7. The remaining two drogued buoys (2581 and 2582) were eventually blown clear of the shallow water; however, because of the recognized reliability problems of the "on/off" indicator, the fate of the drogue is uncertain. It is assumed that the drogues detached.

During early through mid-October there were several periods of strong south to southeast winds; this explains the persistent northward tracks of buoys 2587 and 2581 (5 October, JD 279, to 28 October, JD 302). Both buoys were in heavy sea ice concentrations (9/10 to 10/10), although 2587 was in an area of N/YNG ice, while buoy 2581 was near areas of thicker OLD ice.

A period of remarkably coherent westward movement is apparent in the trajectories of buoys 2581, 2582 and 2587 from 29 October (JD 303) to 30 November (JD 335). During this period, the atmospheric flow in the southern Beaufort Sea was dominated by high pressure in the Arctic Ocean, resulting in persistent winds from the east. The

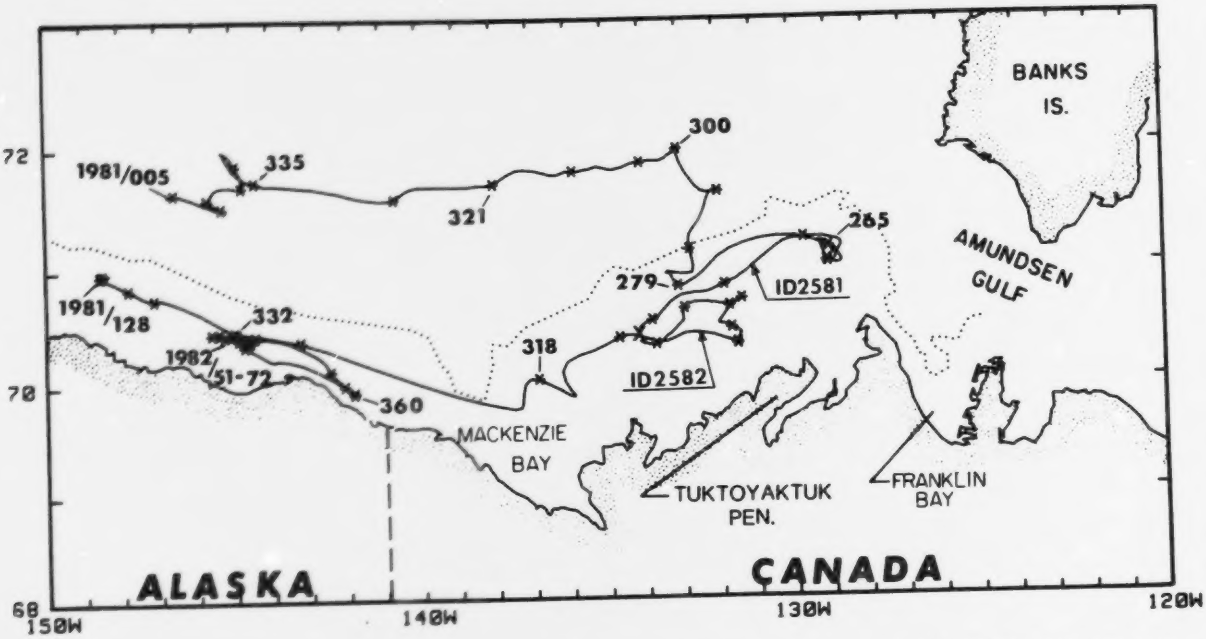

FIGURE 7 FILTERED TRAJECTORIES FOR BUOY 2581 RELEASED 17 AUGUST (JD 230) 1980 AND BUOY 2582 RELEASED 21 AUGUST (JD 234) 1980. THE APPROXIMATE LOCATION OF THE RELEASE SITE IS MARKED BY AN "X". THE DATES ARE GIVEN IN JULIAN DAYS; ASTERISKS ARE PLOTTED AT 7-DAY INTERVALS

average surface wind, as estimated from the pressure distributions of Thorndike and Colony (1981), was 8 m/s. The offshore buoys, 2581 and 2587 (Figures 7 and 6), moved parallel to the coast at approximately 200 km offshore at average speeds of 0.13 m/s and 0.21 m/s, respectively. Both of these buoys moved in 9/10 to 10/10 FY/YNG ice, although the paths were a short distance from and parallel to the 10/10 OLD pack ice. The movement of the inshore buoy (2582) was more complicated, possibly being affected by its proximity to the coast (<50 km) and the Mackenzie River. During one episode (16 November, JD 321, to 22 November, JD 327), the buoy moved rapidly to the west at speeds of up to 0.85 m/s, with an average of 0.60 m/s. This movement occurred in 9/10 to 10/10 YNG/FY ice.

All three buoys continued transmitting positions well into 1982, with rather sluggish motions being interspersed with periods of no motion.

### 1981

The effort in 1981 again focussed on the temporal variability of the surface flow field. As in 1980, eight buoys, four with PRL hulls and four with CANMAR hulls, were released into ice-free water over a 3-week period beginning on 15 August (JD 227). The PRL hulls were fitted with wind speed indicators; the wind data were transmitted with the positions via the ARGOS System. None of the buoys had drogues. On two occasions during the release period, buoys of different hull types were released concurrently to compare their response. On the first date (15 August, JD 227), three buoys, two with PRL hulls and one with a CANMAR hull, were released at the same time. On the second occasion (22 August, JD 234), one of each type was released.

Of the eight buoys launched during 1981, one malfunctioned shortly after deployment and another was apparently recovered by a vessel; the trajectories of the remaining six buoys are plotted in Figure 8 (a, b and c).

The five buoys released in the first week (15-22 August, JD 227-234, Figures 8a and 8b) remained in the general vicinity of the launch area under light and variable winds. This condition persisted until 29 August (JD 241), when 3 days of vigorous winds, primarily from the northwest, drove three of the five buoys ashore on the Tuktoyaktuk Peninsula and the remaining two into Liverpool Bay. The average wind speed measured on buoy 2601 during 29 August (JD 241) to 1 September (JD 244) was 11 m/s. This figure agrees well with an independent estimate of the surface wind speed calculated from the atmospheric pressure distributions presented by Thorndike et al. (1982); the orientation of the isobars was used to estimate the wind direction in the study area.

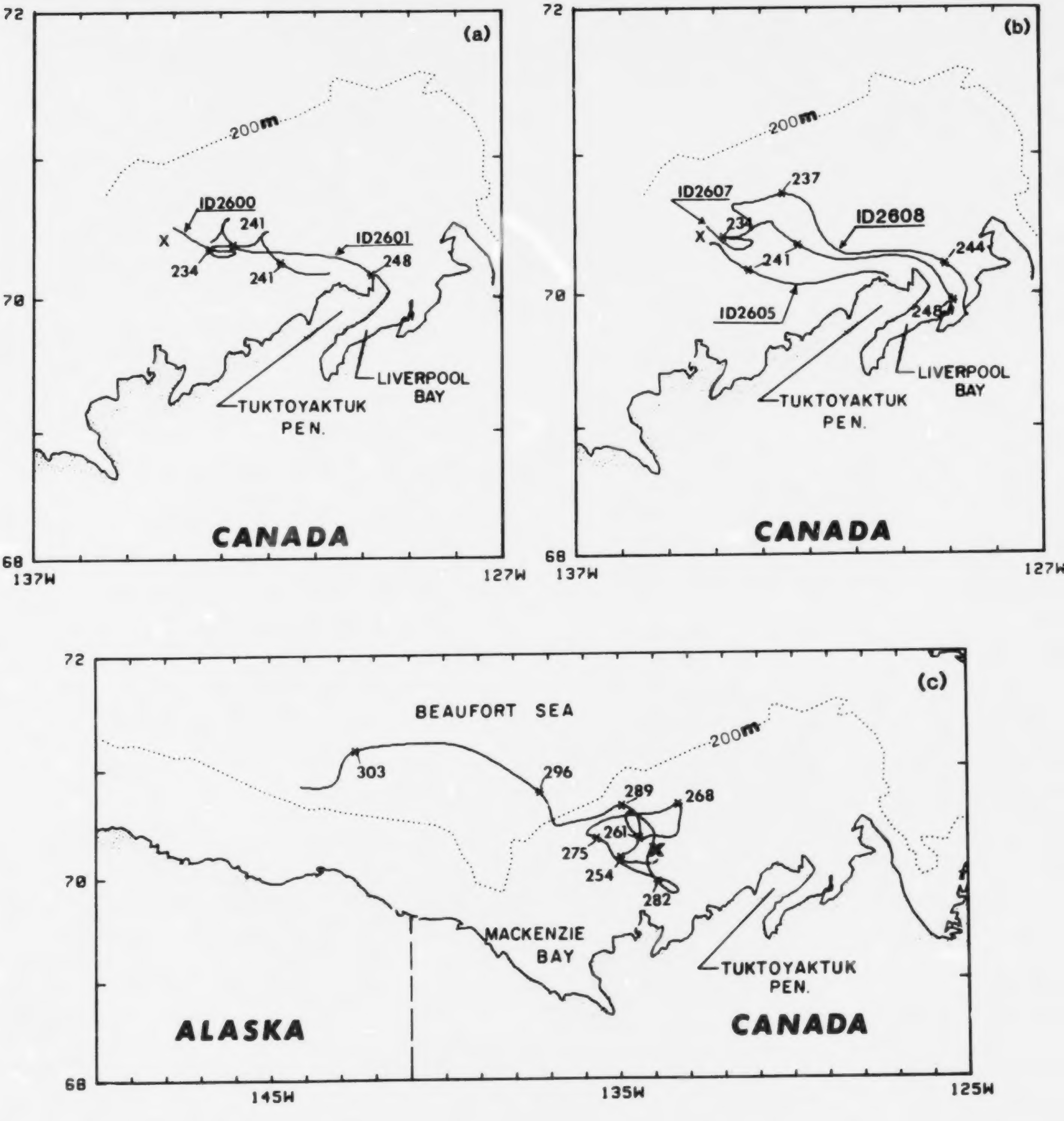
(a)
72
70
68
137W
127W
200m
ID2600
ID2601
X
234
241
241
248
TUKTOYAKTUK PEN.
LIVERPOOL BAY
CANADA
(b)
72
70
68
137W
127W
200m
ID2607
ID2608
ID2605
X
237
234
241
244
248
TUKTOYAKTUK PEN.
LIVERPOOL BAY
CANADA
(c)
72
70
68
145W
135W
125W
BEAUFORT SEA
200m
303
296
289
268
261
275
254
282
X
MACKENZIE BAY
TUKTOYAKTUK PEN.
ALASKA
CANADA

FIGURE 8 FILTERED TRAJECTORIES FOR BUOYS RELEASED IN 1981: (A) BUOY 2600 RELEASED 15 AUGUST (JD 227) AND BUOY 2601 RELEASED 22 AUGUST (JD 234); (B) BUOY 2605 RELEASED 22 AUGUST (JD 234), BUOY 2607 RELEASED 15 AUGUST (JD 227), AND BUOY 2608 RELEASED 18 AUGUST (JD 230); (C) BUOY 2604 RELEASED 4 SEPTEMBER (JD 247). DATES ARE GIVEN IN JULIAN DAYS, ASTERISKS ARE PLOTTED AT 7-DAY INTERVALS

For the four buoys which drifted for the entire northwest wind event (one beached early in the 3-day period), the average shoreward speed was 0.37 m/s. For an 11 m/s wind speed, this results in buoy speeds of 3.4% of the surface wind speed.

The surface currents documented by the eastward buoy movements are remarkably consistent with the flow field proposed by MacNeill and Garrett (1975) for persistent and vigorous (≥12 m/s) northwest winds. This current regime, based on observations and extrapolations, provides for a general surface water movement southeastward toward the coast which turns parallel to the coast about 10 km offshore. They estimate a mean surface current speed of 0.35 m/s, and also propose a circulation into Liverpool Bay. The raw buoy position data (Figure 9) offer a more dramatic case than the filtered data for the existence of a coastal current along the Tuktoyaktuk Peninsula and the motion into Liverpool Bay. One could have accurately predicted the buoy motions based on the current field of MacNeill and Garrett (1975).

Buoy 2604, released on 4 September (JD 247), well after the northwest winds had subsided, showed quite a different behaviour (Figure 8c). It remained in the general launch vicinity for 6 weeks, whereupon it commenced a persistent and, at times, rapid (~0.50 m/s) northwest and westward movement (25 October, JD 298) under the influence of east winds. During this period, the buoy was in 9/10 to 10/10 YNG ice; it ceased transmitting shortly after it entered an area of 9/10 to 10/10 OLD/FY ice on 4 November (JD 308).

There was little apparent difference in the movement of the PRL and CANMAR hulls. In the two cases in which a buoy of each type was released concurrently, the buoys moved in a qualitatively similar manner; a detailed analysis has not been completed. Regretably, the effort to compare the movement of identical hulls with the concurrent movement of different hull types failed with the early demise of one of the PRL-hulled buoys released on 15 August (JD 227).

## DISCUSSION AND CONCLUSIONS

The most striking feature of the buoy drift data is the dramatic inter-annual variability evident in the trajectories. Buoys deployed in essentially the same location travelled as far west as the Wrangel Island vicinity in the Chukchi Sea and as far east as the Parry Peninsula in Amundsen Gulf. Preliminary comparisons of the early buoy movement data and surface winds calculated from NMC atmospheric pressure distributions (Murphy et al., 1981) suggest that the buoy motions are closely related to local wind forcing. More detailed comparisons are presently being conducted using the pressure distributions determined by the University of Washington Polar Science Center (Thorndike and Colony, 1981). Their efforts in deploying numerous satellite-tracked platforms with barometers on sea ice have vastly improved the quality of meteorological data in the Arctic Ocean.

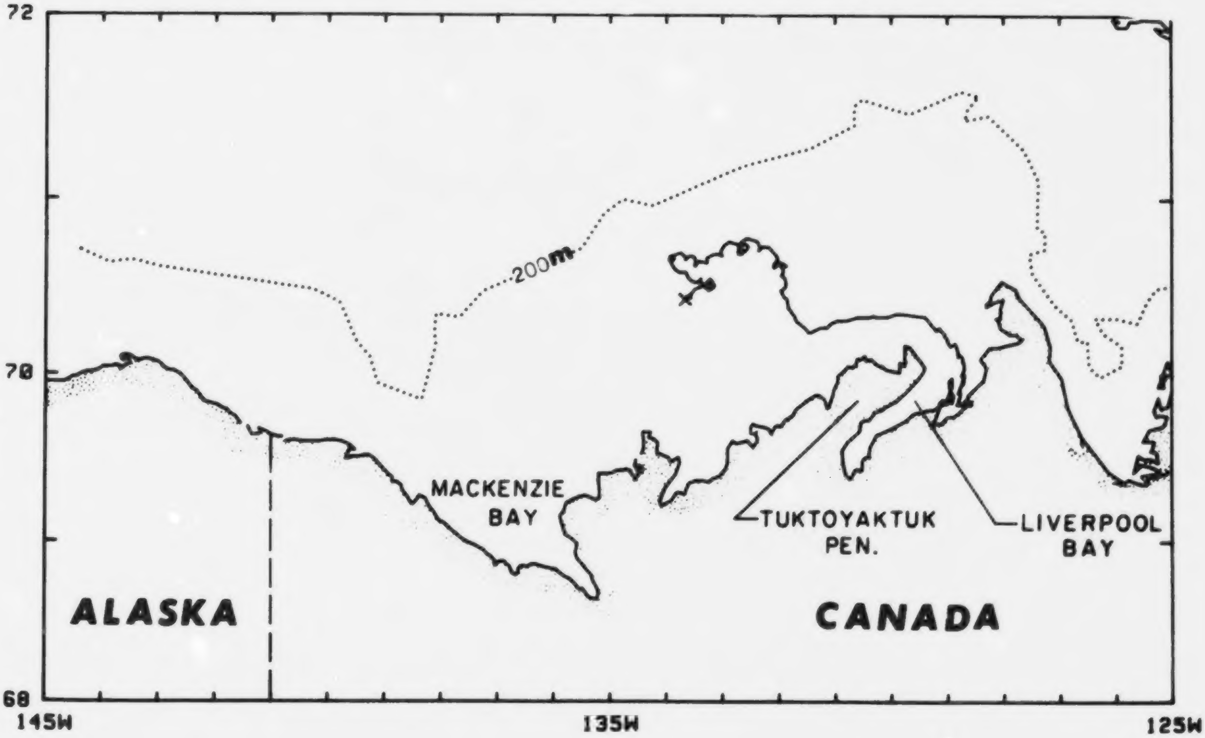

FIGURE 9 RAW BUOY POSITION DATA FOR BUOY 2608 RELEASED 18 AUGUST (JD 230) 1981

Amid the pronounced inter-annual variability demonstrated by the buoy trajectories, there is a thread of consistency. In all of the years, significant net westward movement has been evident in the buoy tracks. By far the most dramatic westward movement occurred in 1979; all of the buoys moved to the west, one approaching to within 50 km of Pt. Barrow (443). In 1980, three of the four buoy tracks showed a net westward motion, and one of these (2582) approached to within 10 km of the Alaskan coast. Even in 1981, with the spectacular eastward movement, the buoy released after the strong northwest winds had subsided (2604) had a net westward motion. It is not the intent to argue that these buoy motions reflect the movement of oil from potential spills, but rather to show that there can be significant westward net drift in the southeastern Beaufort Sea and that there is some justification for the concern that the Alaskan coast could be affected by a major blowout during Canadian operations.

The eastward motion in the 1980 and 1981 trajectories provides strong support for the surface current regime proposed by MacNeill and Garrett (1975) for persistent northwest winds in the Tuktoyaktuk area. Northwest winds, usually associated with the passage of low pressure systems through the northern Beaufort Sea, are a common but not dominant summer wind condition in the study area. They are important because vigorous and persistent northwest winds cause rapid onshore movement of surface waters. The 1981 drift data, in particular, support the onshore motion and the development of a strong coastal current flowing northeastward along the Tuktoyaktuk coast, and eventually into Liverpool Bay.

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# DETECTION OF OIL-UNDER-ICE - A JOINT ESSO/EPS PROJECT

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## INTRODUCTION

Since the early part of the last decade, when oil exploration offshore in the Beaufort Sea was being proposed, a need was recognized for detecting oil-under-ice. Studies conducted as part of the Beaufort Sea Project (NORCOR, 1975) demonstrated that oil deposited under ice would become encapsulated in the ice for significant periods of time. The oil would move with the ice; in spring, it would rise to the surface and collect in melt pools. Numerous experiments have been performed to understand the process involved in detecting oil in first year ice (Dickens and Buist, 1981), in multi-year ice (Comfort and Purves, 1982) and in the laboratory (Rosenegger, 1975; Green et al., 1977; Metge, 1978). These efforts clearly demonstrated that, in order to track the oil, it was only necessary to monitor the ice. An early AMOP program (Goodman, 1978) recommended a system of micro and macro buoys for this purpose. These systems have since been developed (McGonigal and Wright, 1977; Roddis, 1980) and are routinely used for ice motion monitoring.

If the ice floes should break or diverge, as might occur in the shear zone, it would be useful to detect the presence of oil in or under the ice. Such a system would enable the routine monitoring of subsea under-ice pipelines and the detection of pollution near northern loading terminals and production platforms. The difficulties of detecting pipeline leaks under ice were identified as a concern of the Normal Wells Environmental Assessment Review Panel. This paper will present a background and overview of the limitation of oil-under-ice detection systems and indicate possible improvements.

## BACKGROUND

Detecting oil-under-ice is related to the more general problem of measuring ice thickness. These techniques have been studied by many workers and are reviewed by Kovacs (1977). Both acoustic and electromagnetic sounders have been successful. Electromagnetic ice thickness measuring equipment operating between 100 and 1,000 MHz are now routinely used for sea ice thickness determination. The problems of coupling acoustic energy into the ice are severe; ultrasonic systems have thus not been used to a great extent.

This paper is restricted to the detection of oil from the ice surface; it is therefore essential to have the sensing radiation penetrate the ice. The parameters for doing this have been defined by ice thickness measurement experiments. A study, financed by industry and government under the auspices of the Environmental Protection Service, was commissioned to determine the feasibility of several oil-under-ice detection techniques (Gill, 1979). A number of methods, including radio frequency and acoustic echo systems and the use of gamma rays, were examined. It was concluded that each sensor had potential, but that a theoretical understanding of the signal generation process was lacking. The Environmental Protection Service supported an unsolicited proposal (Remotec, 1979) to undertake a laboratory study of these sensors using both fresh and saline ice in a laboratory flume. A comparison was made between signal returns from the ice with and without oil at the ice-water interface. Sensors used were a GSSI radar, normally used for ice thickness measurement, a passive VHF radio spectrometer, a passive gamma ray spectrometer, and an ultrasonic inspection unit. Except for the ultrasonic inspection unit, none of these sensors gave a significantly different signal with the presence of oil at the ice-water interface than when there was no oil. The ultrasonic system, operating at frequencies between 0.5 and 2.25 MHz, gave different returns when oil was present under freshwater ice. The Remotec report does not speculate as to the nature of the return signal or its origin. The acoustic impedance of oil, ice and seawater are similar, hence only a weak reflection should occur at these interfaces.

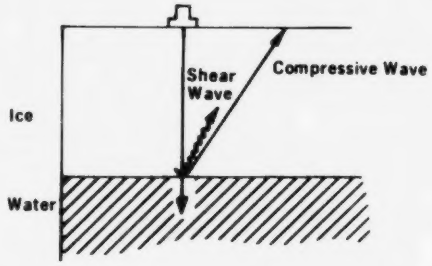
The lack of signal difference for the impulse radar was unexpected. Several experiments have indicated that such radars could detect the presence of oil under some conditions (Dickens and Buist, 1981; Goobie et al., 1981; Mann, 1979; Gill, 1979; Kovacs, 1977). None of these authors determined the cause of this reflection, nor did they quantify the conditions under which the signal would be observed. The time resolution required for a 1 cm thick layer of oil is 5 ps ($5 \times 10^{-12}$ s), which is four orders of magnitude shorter than the time resolution of the impulse radar systems. The strength of signal return at the ice-oil interface is on the order of 0.07, compared to 0.6 for the ice-water interface, an order of magnitude difference. The ice-water reflection coefficient will approach unity for seawater since it is a conductor. Since the oil will naturally move to areas of reduced ice thickness (Cox and Schultz, 1981), another possible interpretation of the reported impulse radar results is that the ice was thinner where the oil was present, giving an anomalous signature. The oil fills in the under-ice cavities, thus generating a smooth, flat reflector when compared to the ice-water interface. As demonstrated by Beckman and Spizzichino (1963), an enhancement in return signal of at least a factor of 10 can occur for an infinite reflector as compared to a reflector with a roughness amplitude in the order of a few wavelengths. Gill (1979) proposed that the effect was due to a phase shift at the interface when an insulator was present, since oil and seawater differ in conductivity by six orders of magnitude. The existing systems are incapable of measuring such a phase shift, which has a time scale of a few nanoseconds (1 ns = $10^{-9}$ s). As with acoustics, the exact process involved in generating different return signals from the ice-oil and ice-water interfaces is not understood.

A third detection method was investigated by Rice University (Rivet, 1981) under the sponsorship of Exxon. This study indicated that the fluorescence spectrum of oil can be readily distinguished from that of natural sea ice. Using a 22 cm thickness of natural sea ice from Alaska, the laser-induced fluorescence spectra of oil and oil-under-ice were seen to be similar in character, with the ice causing only attenuation in signal strength. The results of these experiments show that the laser will penetrate up to 2 m of ice. The laser fluorescence technique and the acoustic technique are not adaptable to aircraft remote sensing; they are limited to ice surface measurements.

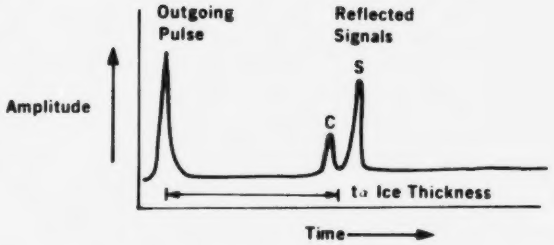
In 1980, Esso Resources Canada Limited (ERCL) and the Environmental Emergency Branch (now the Environmental Emergencies Technology Division (EETD)) of the Environmental Protection Service entered into an agreement to jointly continue research in methodologies to detect oil-under-ice. The remainder of this paper describes this work. The mechanism of acoustic return from the ice-oil interface, the cause of the impulse radar returns, and the development of a practical system to detect oil-under-ice still must be resolved.

## ACOUSTIC SYSTEMS

The understanding of the acoustic results reported by Remotec (1979) would require the examination of the acoustic characteristics of oil, sea ice and seawater. This work was contracted to Dr. Hugh Jones of Dalhousie University and reported at the 1982 AMOP Technical Seminar (Jones and Kwan, 1982). It was demonstrated, as a result of this theoretical and laboratory study, that transverse waves can be propagated by the ice-oil interface, whereas they are not transmitted by the ice-water interface. The oil is much more viscous than the water, which accounts for the transmittal of the transverse or shear waves. The reflection coefficient of the compressive wave is about the same for the two interfaces, so one must develop techniques for separating the two waves. Since the shear waves travel at about half the velocity of compressive waves, it would seem they would be readily distinguished by an analysis of the time delays. The hypothetical returns are illustrated in Figures 1 to 3.



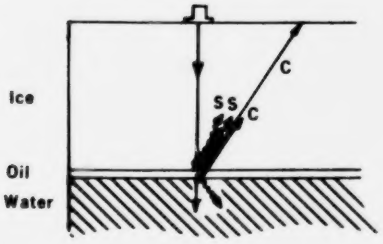
Situation



C = Compressive Wave
S = Shear Wave

Anticipated Signal Return

FIGURE 1 HYPOTHETICAL SIGNAL RETURNS FOR THE WATER ONLY UNDER ICE SITUATION



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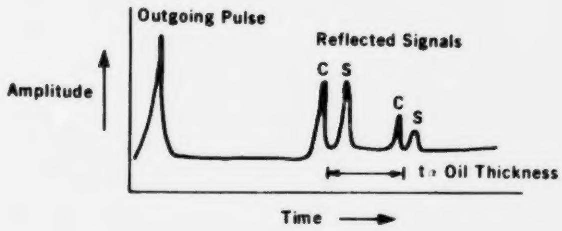


Anticipated Signal Return

C = Compressive Wave
S = Shear Wave

FIGURE 2 HYPOTHETICAL SIGNAL RETURNS FOR THE OIL-UNDER-ICE SITUATION

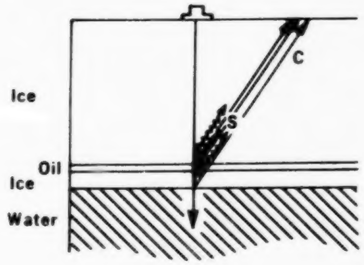
The ultrasonic flow inspection equipment used by Remotec (1979) operated at frequencies of 0.5, 1.0 and 2.25 MHz and succeeded in penetrating the ice. In order to optimize the acoustic system, a study was made by Jones and Kwan (1982) of the optimal frequency for oil detection and ice penetration, which are competing processes. High frequencies give good spatial resolution and the capability of detecting thin films, while low frequencies are better for propagation through the ice. A frequency in the region of 100 kHz has been found to be a good compromise between spatial resolution (about 3 cm) and attenuation.

The next problem is to separate the compressive and shear waves. In order to understand the problem, it is necessary to estimate the order of the time delay, as illustrated in Figure 4. The minimum working thickness for vehicle traffic on ice is about 30 cm, so the required time resolution is in the order of 0.2 ms, which is 20 cycles at 100 kHz. Since the capability of a transducer to respond is proportional to Q of the output circuit, this implies a low Q system, which in turn means a broadband output signal. In order to receive such a pulse, a wide band receiver with its intrinsic poor signal-to-noise ratio would be necessary. Noise causes interference with the timing, and hence reduces the ability to discriminate between compressive and shear waves. Jones and co-workers at Dalhousie have developed a special transducer which, when operated at a low pulse-repetition rate (500 pps), does not ring and can be used to discriminate between the compressive and shear waves.

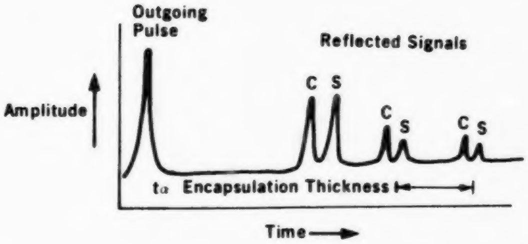
Recent advances in the understanding of ultrasonics in oil and ice detection will be presented by Jones (1983) in this session. The electronic problems associated with designing and operating an acoustic system in the field are being addressed by Knudsen (1983) and are also discussed in this session.

## ELECTROMAGNETIC SYSTEMS

Field observations appear to indicate that an impulse radar would be the most likely system to detect oil-under-ice. It has a demonstrated capability to measure ice thickness and is the only technique that would offer an airborne remote sensing capability (Dean, 1981).



Situation



Anticipated Signal Return

C = Compressive Wave.
S = Shear Wave

FIGURE 3 HYPOTHETICAL ACOUSTIC SIGNAL RETURNS FOR THE OIL-ENCAPSULATED-UNDER-ICE SITUATION

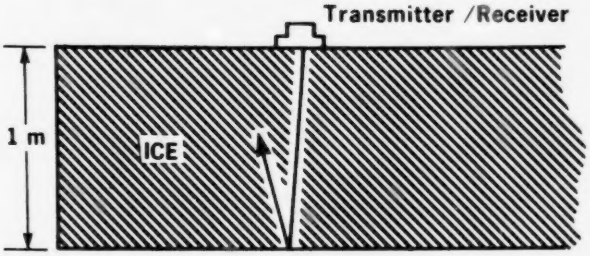
The relevant properties of the various materials involved in the oil-under-ice problem are summarized in Table 1. In order for an interface to be detected, there must be a significant difference between the dielectric constants of the materials or their conductivity. The physical placement of the various layers is critical in order to achieve an adequate return signal.

As with the acoustical case, factors which need to be considered are the penetration of the ice and the generation of a unique return at both the oil-ice and ice-water interfaces. The attenuation of sea ice as a function of frequency is shown for various types of sea ice (Figure 5). Most radar systems have a system performance of about -100 db, so for a 2 m ice sheet, the attenuation should be less than 25 db/m. This implies a low salinity, cold ice such as is typical of the Arctic environment. In order to achieve adequate spatial resolution, wave length (g) should be between 3 and 10 cm, thus electromagnetic sensors operate at frequencies between 300 and 1,000 MHz. It is clear from Figure 5 that freshwater and multi-year ice will give better results than first year ice due to their lower attenuation.

Four types of signal return can be used to detect the presence of oil under ice:

a) out-of-phase returns due to the low conductivity of oil;
b) large amplitude returns due to construction interference effects;
c) spatial dependence of amplitude of return signals due to interference effects;
d) conductivity differences.

Phase measurements of these frequencies are difficult, since the times involved are in the order of nanoseconds. Dispersion and multipath returns could be confused with interface phase changes and thus render a unique interpretation impossible. While simple in principal, phase measurements are difficult. This approach will not be investigated further at this time.



Velocity of waves: 3,000 m/s compressive (3 m/ms) c
1,500 m/s shear (1.5 m/ms) s

Total transmit

$$tc = \frac{2t}{Vc}$$

$$Ts = \frac{T}{Vc} + \frac{T}{Vs}$$

$$\Delta T = Tc - Ts = t\left\{\frac{2}{Vc} - \frac{1}{Vc} - \frac{1}{Vs}\right\}$$

$$= t\left\{\frac{1}{Vc} - \frac{1}{Vs}\right\}$$

$$\Delta t(ms) = t\left\{\frac{1}{3} - \frac{1}{1.5}\right\} = \frac{t}{1.5}$$

FIGURE 4 EXAMPLE OF TIME DELAY CALCULATION

TABLE 1 SUMMARY OF PROPERTIES RELEVANT TO THE RADIO FREQUENCY DETECTION OF OIL-UNDER-ICE (Dean, 1981; and present authors)

| Media | Approximate Conductivity (siemens/m) | Approximate Dielectric Constant) |
|---|---|---|
| Air | 0 | 1 |
| Freshwater | $10^{-4}$ to $3 \times 10^{-2}$ | 81 |
| Seawater | 4 to 5 | 81 to 88 |
| Freshwater Ice | $10^{-4}$ to $10^{-2}$ | 4 |
| Seawater Ice | $10^{-2}$ to $10^{-1}$ | 4 to 8 |
| Snow | $10^{-5}$ to $10^{-2}$ | 1 to 4 |
| Oil | $10^{-9}$ to $10^{-6}$ | 2 |

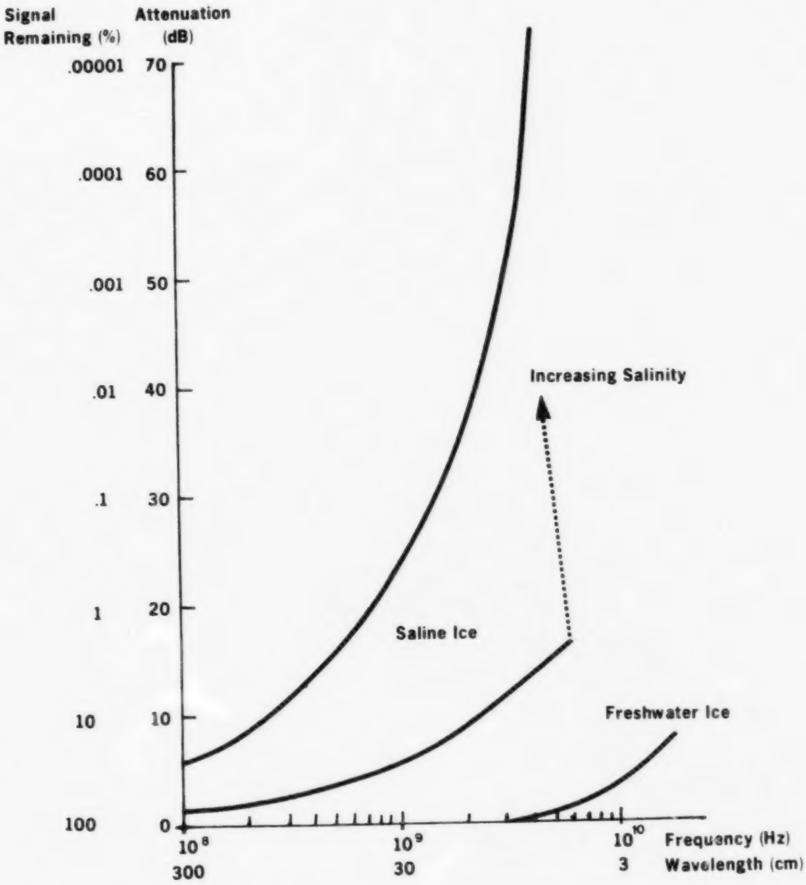


FIGURE 5 EXAMPLES OF ATTENUATION VERSUS FREQUENCY

The interference effects can be computed using a model in which the signals propagate across a series of plane dielectric layers. Each layer represents a potential surface (Jackins et al., 1982) and the returns are a measure of the properties of the individual layers. By using an impulse radar and a fast-Fourier transform of the return signal, the layer structure can be determined. This will be discussed later in this session by Dean (1983).

The third method of detecting the oil-under-ice would be to measure the spatial dependence of the return signal. There will be a series of constructive and destructive interference patterns which will be different for the presence of oil. This is an indirect method of measuring the 1/2 phase change discussed earlier. Such effects have been noted on a vaster scale by glaciologists using radio echo sounding equipment (Robin et al., 1969).

## CONCLUSION

This is, in a sense, an interim report, describing the present state of knowledge of the detection of oil-under-ice. One of the main problems is to understand the signal sources for both acoustic and electromagnetic radiation. The identification by Jones and Kwan (1982) of the presence of shear waves in the return is a major advance. The use of resonant scattering theory by Jackins et al. (1982) is significant, but requires experimental verification such as Dean (1983) is undertaking. There are still electronic design problems with the acoustic systems which must be resolved, and this is being investigated by Knudsen (1983). The ability to detect oil-under-ice is a needed technology and important advances have been made in the understanding of the problems, with identified signal sources which can detect oil-under-ice. The authors confidently hope that, in a few years, a reliable and practical system can be developed.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of Esso Resources Canada Limited and Environment Canada; both have provided laboratory and test facilities that have been used in these experiments. The work of Dr. Hugh Jones and his graduate students at Dalhousie University, Halifax; Mr. Don Knudsen of Knudsen Engineering of Richmond, Ontario, and Mr. Arnold Dean of Dean Engineering of West Farley, Vermont, provides the essential high quality scientific and technical results. Their effort is duly acknowledged and appreciated.

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# THE DETECTION OF CRUDE OIL UNDER SEAWATER IN THE ARCTIC OCEAN

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## ABSTRACT

This paper describes theoretical and experimental studies on the detection of crude oil under Arctic seawater ice. The measurement of the visco-elastic properties of oil is described; data are presented for different frequencies. The data from these measurements have been used to obtain the amplitudes of the reflected components of the ultrasonic waves (shear and compressional) for both an incident compressional and shear wave at the ice-oil interface. The significance of these results for the detection of oil is discussed. Additionally, work which has been done on the design and performance of ultrasonic transducers for use on ice is described. Some comments on proposed further work are given.

## INTRODUCTION

Methods of determining the location and extent of oil pools trapped under Arctic sea ice have been previously reported (Jones and Kwan, 1982). Several developments have since taken place. First, it was decided to investigate the visco-elastic properties of crude oil. In the pilot study, the oil had been treated as a Newtonian liquid, but this is only a rough approximation. A more exact treatment requires the viscous and shear properties of the oil to be established (Barlow and Lamb, 1959). To this end, a series of experiments were undertaken to measure the visco-elastic properties of crude oil. The oil was shown to have a shear modulus with real and imaginary parts; consequently, it was able to support a shear wave. This factor changes the interfacial effects; a detailed study of this problem has therefore been attempted, treating the oil as an equivalent solid. The more difficult problem of dealing with the complex shear modulus remains to be attempted. However, we are now in a position to say what the limiting performance of the ultrasonic measurements should be and we can also make a reasonable assessment of the effectiveness of shear wave searches. Consideration is also given to the design of ultrasonic transducers for use on ice.

## PROPERTIES OF OIL

The stress-strain relationship of many fluids has been the subject of many studies. A recent paper (Lamb, 1972) reviews work on a wide range of liquids. The nature of the relationship between the real and imaginary parts of the complex compliances as a function of frequency and temperature and pressure have been established. Figure 1 shows normalized components of a range of liquids. It is noted that the shear mechanical impedance is:

$$Z_L = R_n + jX_n \tag{1}$$

and the complex shear compliance, $J^*$, is related to $R_n$ and $X_n$ by (2) and (3) below:

$$J^*(j\omega) = J' - jJ'' \tag{2}$$

$$J' = \frac{\rho(R_n{}^2 - X_n{}^2)}{(R_n{}^2 + X_n{}^2)^2}, \qquad J'' = \frac{2\rho R_n X_n}{(R_n{}^2 + X_n{}^2)^2} \tag{3}$$

In the elastic region, $X_n \simeq 0$, hence $J'' \simeq 0$. In the viscous region, $J' = 0$ (i.e., $R_n = X_n$, so that $J' = 2\rho/R_n{}^2 = 4/\omega\eta$).

Our experiments are primarily concerned with the isothermal conditions in which the crude oil is held at a constant temperature at approximately the melting or freezing point of sea ice; consequently, it is not necessary to inquire into the temperature dependence of the properties but simply to measure the real and imaginary parts of the shear modulus directly or indirectly.

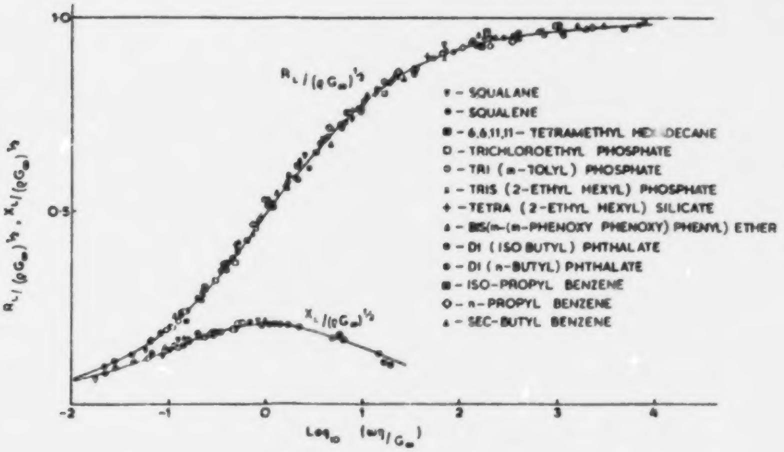

FIGURE 1 NORMALIZED PLOTS OF RESISTIVE AND REACTIVE COMPONENTS OF A NUMBER OF LIQUIDS (from Lamb, 1972)

If we write:

$$(\nabla^2 + k^2)p = 0 \tag{4}$$

and suppose that the quantity k relates to the appropriate visco-elastic constant, then

$$k = k'-j\alpha \tag{5}$$

which leads to

$$p = p_0 e^{-\alpha x} e^{j(\omega x - k'x)} \tag{6}$$

for a wave in the x direction with a frequency characterized by $\omega$. It can be seen that the real and imaginary parts of k can be identified from the velocity of propagation and the absorption coefficient.

In our experiment on crude oil, we were at a disadvantage because of the difficulties in obtaining suitable shear wave transducers initially. We overcame this problem by making a wedge-shaped transducer which produced shear waves over a suitable range of frequencies. Figure 2 shows the layout of the apparatus. It consists of a tank (Figure 3) which is lined to make it anechoic. A thickness oscillator is coupled via a polystyrene wedge to an aluminum guide. The face of this guide is in contact with the crude oil in the tank; shear waves are transmitted via the oil to an aluminum rod which can be slid backwards and forwards to vary the distance travelled by the shear waves. This rod has a small thickness-sensitive transducer mounted on its upper side to detect the passage of shear waves in the rod. The rod was made sufficiently long for end-reflected shear waves to be of little consequence.

The tank was used to obtain data on the velocity and absorption of the shear waves by varying the distance that they travelled through the oil (Figure 4). The results of these experiments, summarized in Table 1, have been used in the later stages of this paper. At this time, a new apparatus, originating from Mason et al. (1949), McSkimin (1952) and Barlow and Lamb (1959), is being assembled. This apparatus is shown in Figure 5. Measurement of the phase and amplitude changes of the reflected shear waves in the presence of oil gives the necessary data.

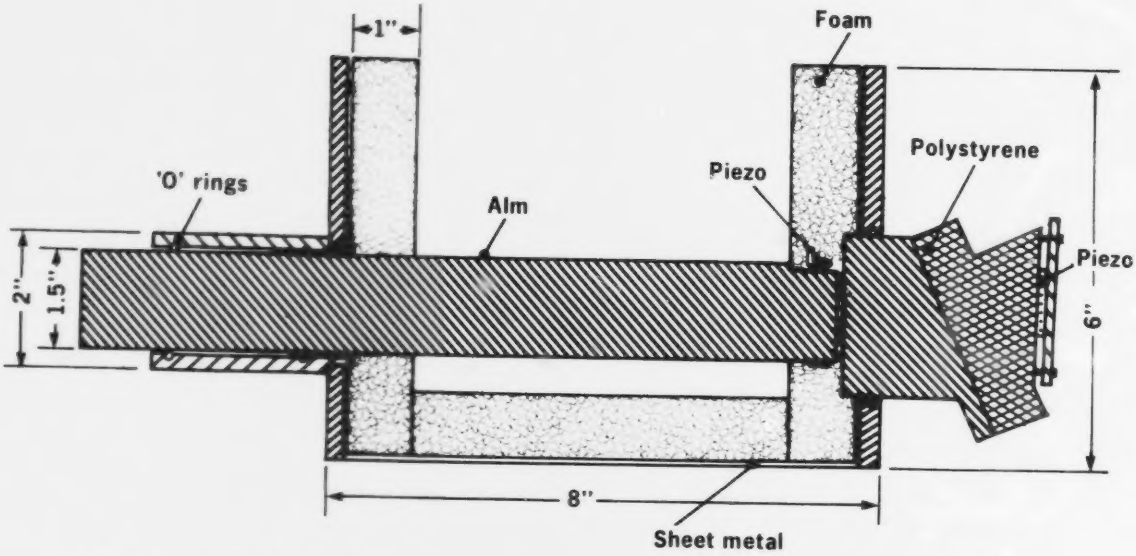
1"
Foam
Polystyrene
'O' rings
Piezo
Alm
Piezo
2"
1.5"
6"
8"
Sheet metal

FIGURE 2 SHEAR WAVE TANK

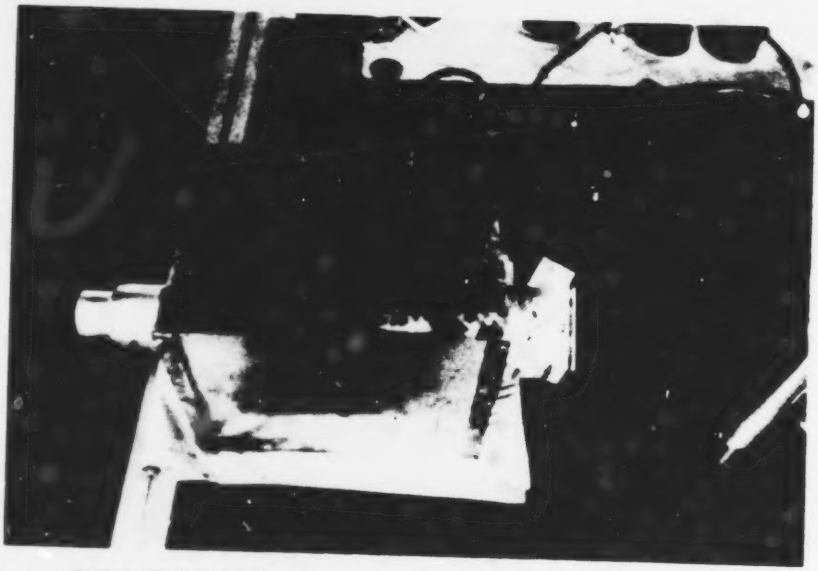

FIGURE 3 SHEAR WAVE APPARATUS

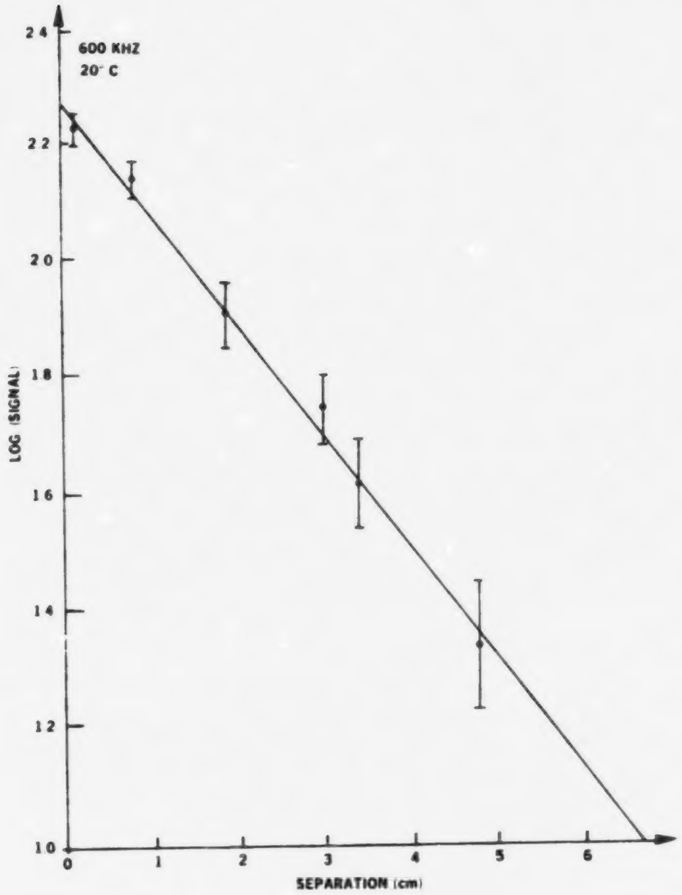

FIGURE 4 SHEAR WAVE ATTENUATION IN CRUDE OIL

TABLE 1 SHEAR PROPERTIES OF CRUDE OIL

| Frequency | Cs | Attenuation Coefficient |
|---|---|---|
| 200 kHz | 450 m/s | $40 \times 10^{-6}$ |
| 600 kHz | 500 m/s | $44 \times 10^{-6}$ |
| 1 MHz | 500 m/s | $37 \times 10^{-6}$ |
| 1.5 MHz | 500 m/s | - |

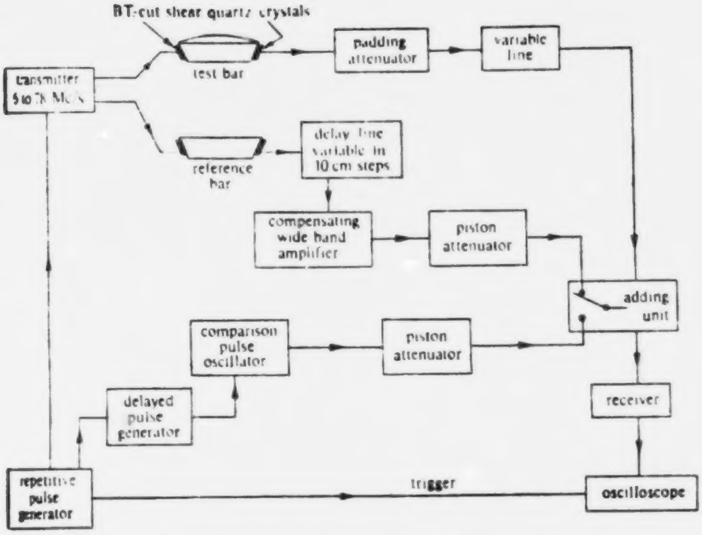
BT-cut shear quartz crystals
test bar
padding attenuator
variable line
transmitter 5 to 78 Mc/s
reference bar
delay line variable in 10 cm steps
compensating wide band amplifier
piston attenuator
adding unit
comparison pulse oscillator
piston attenuator
delayed pulse generator
receiver
repetitive pulse generator
trigger
oscilloscope

FIGURE 5 SCHEMATIC DIAGRAM OF THE MEASURING SYSTEM
(From Barlow and Lamb, 1959)

## INTERFACIAL EFFECTS ON ULTRASOUND AT OIL/ICE SURFACE

The reflection and transmission of sound at an interface between two materials is often an extremely complex affair (Ergin, 1952; Mott, 1970; Cooper, 1967). Figure 6 shows the general geometry of the conditions which exist when a shear or longitudinal wave is incident on the boundary between two solids. It can be shown that the ratio (if $\psi'' = 0$):

$\phi'/\phi'' = V_u/\ell\ell$ (the amplitude ratio of the reflected compressional wave to the incident wave)

$$\Delta V_u/\ell\ell = A_1^2 - \beta A_2^2/\alpha + (\alpha_1/\beta_1)(B_1^2 - \beta B_2{}^2/\alpha) + m(\beta_1/\beta - \alpha_1/\alpha)(\kappa_1^4/4\xi^4) \tag{7}$$

where

$$\Delta = A_1^2 + \beta A_2^2/\alpha + (\alpha_1/\beta_1)(B_1^2 + \beta B_2^2/\alpha) + m(\alpha_1/\alpha + \beta_1/\beta)(\kappa_1^4/4\xi^4)$$

the angles being related by Snell's law so that:

$\alpha = \kappa\cos\theta$

$\alpha_1 = \kappa_1\cos\theta_1$

$\xi = \kappa\sin\theta$

$A_1 = n^2 - mP_2/\xi$

$B_1 = (n^2 - m)B_2/\xi$

$P_1 = -\kappa\cos 2\beta/2\sin\beta$

$\beta = \kappa\cos\gamma$

$\beta_1 = \kappa_1\cos\gamma_1$

$m = \rho_1/\rho_2$

$A_2 = (n^2 P_1 - mP_2)/\beta$

$B_2 = (\beta_1/\beta)(n^2 P_1/\xi - m)$

$n = v_{1s}/v_{2s}$ (ratio of shear velocities)

$P_2 = -\kappa_1\cos 2\zeta/2\sin\zeta$

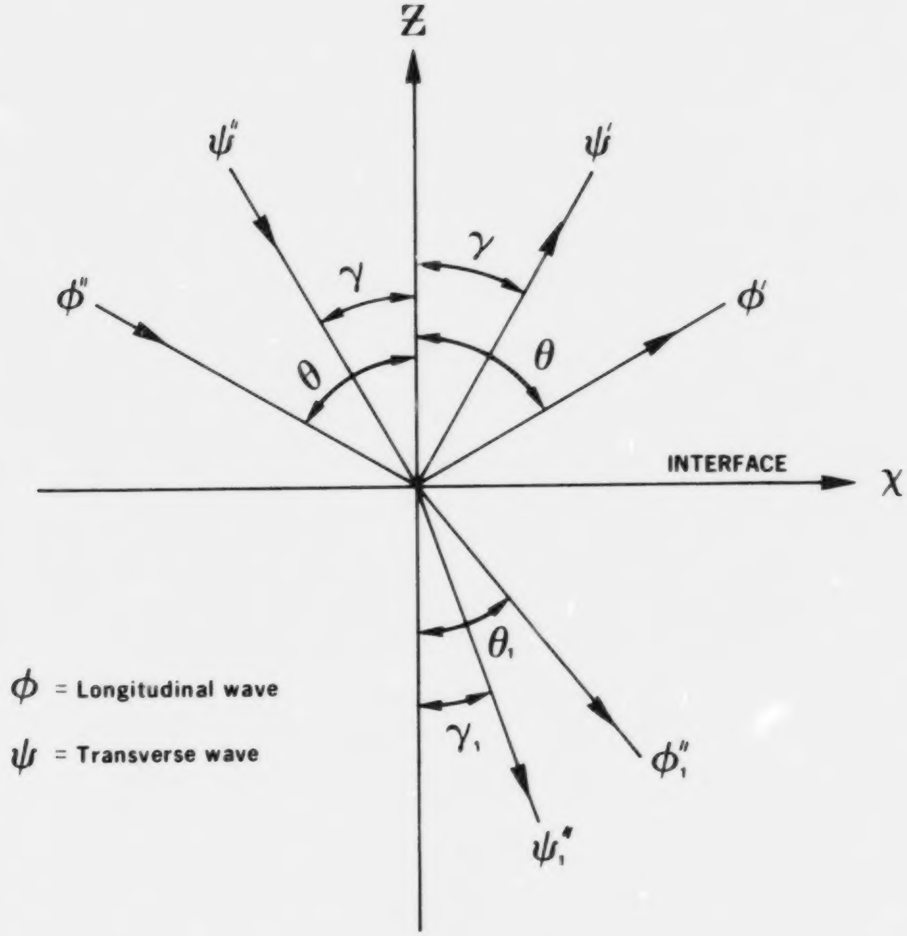
Z
ψ''
ψ'
γ
γ
φ''
φ'
θ
θ
INTERFACE
χ
θ₁
γ₁
φ₁''
ψ₁''
φ = Longitudinal wave
ψ = Transverse wave

FIGURE 6 LABELLING CONVENTIONS

In the case of the shear wave generated at the boundary

$4'/Q'' = \quad V_{\ell t}$

$$-(\Delta/2)V_{\ell t} = A_1A_2 + (\alpha_1/\beta_1)B_1B_2 \tag{8}$$

In the case of a shear wave incident on the boundary (i.e., $\phi'' = 0$), then writing $V_{tt} = \psi'/\psi''$ and $V_{t\ell} = \phi'/\psi''$, it can be shown that:

$$\Delta V_{tt} = (\alpha_1/\beta_1)(B_1^2 - \beta B_2^2/\alpha) + A_1^2 - \beta A_2^2/\alpha + m(\alpha_1/\alpha - \beta_1/\beta)(\kappa_1^4/4\xi^4) \tag{9}$$

and

$$\Delta V_{t\ell} = -2\beta/\alpha(A_1A_2 + (\alpha_1/\beta_1)B_1B_2).$$

These equations are substantially different from those for a liquid/solid interface (Jones and Kwan, 1982) and the significance of their evaluation for the circumstances of this study was explored using the data in Table 1.

In the first instance, the ratio of the reflected compressional wave and its associated shear wave was determined for the two cases, i.e., sea ice in contact with seawater and, secondly, sea ice in contact with oil. Figure 7 shows the comparison between the two cases. The ratios between the two cases are significantly different and this point is illustrated in Figure 8. Clearly this substantial difference should be obvious in practice and should lead to the discovery of oil pools trapped under the ice.

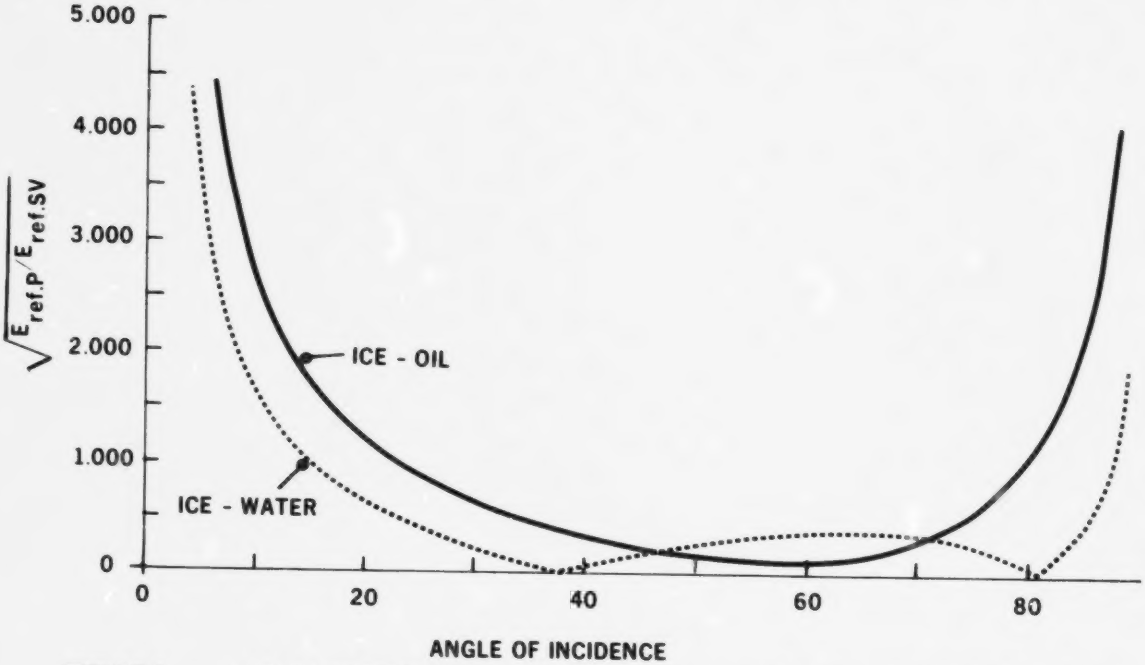

FIGURE 7 P WAVE INCIDENT IN SEA ICE AGAINST OIL OR WATER (square root of the energy ratio of the reflected P wave to the reflected SV wave vs incident angle. The oil is considered as a solid)

An alternative approach is the use of shear waves instead of compressional or longitudinal waves. Figure 10 shows the comparison between sea ice/seawater and sea ice/oil cases; this figure is the shear wave equivalent of Figure 7. Figure 11 shows the ratio of the ratios plotted in Figure 10; it is equivalent to Figure 8. Clearly, incident shear waves would reveal the same information as compressional waves, but the results for the angles of incidence of interest (0-20°) would not be as clear cut as the compressional waves data. As it is more difficult to launch shear waves into ice than compressional waves, it appears that compressional waves are more useful for the detection of oil on two counts.

## TRANSDUCERS FOR ICE APPLICATIONS

The development of transducers to work in the range of 100 kHz to 1 MHz has been undertaken. The lower frequencies were of interest for field trials and the higher frequencies for laboratory work. The desirable quantities were that the transducer should couple closely to the ice and should not "ring". Only two compressional wave transducers were studied. The needs of the measurements would best be served by a very short ultrasonic pulse, because this would allow the shear and compressional components to be identified with greater ease. The compressional velocity is roughly twice that of the shear velocity; consequently, the difference in arrival times of the two signals is about 300 μs for ice 0.5 m thick. This means that the received pulse should not be larger than 3-4 wavelengths at 100 kHz.

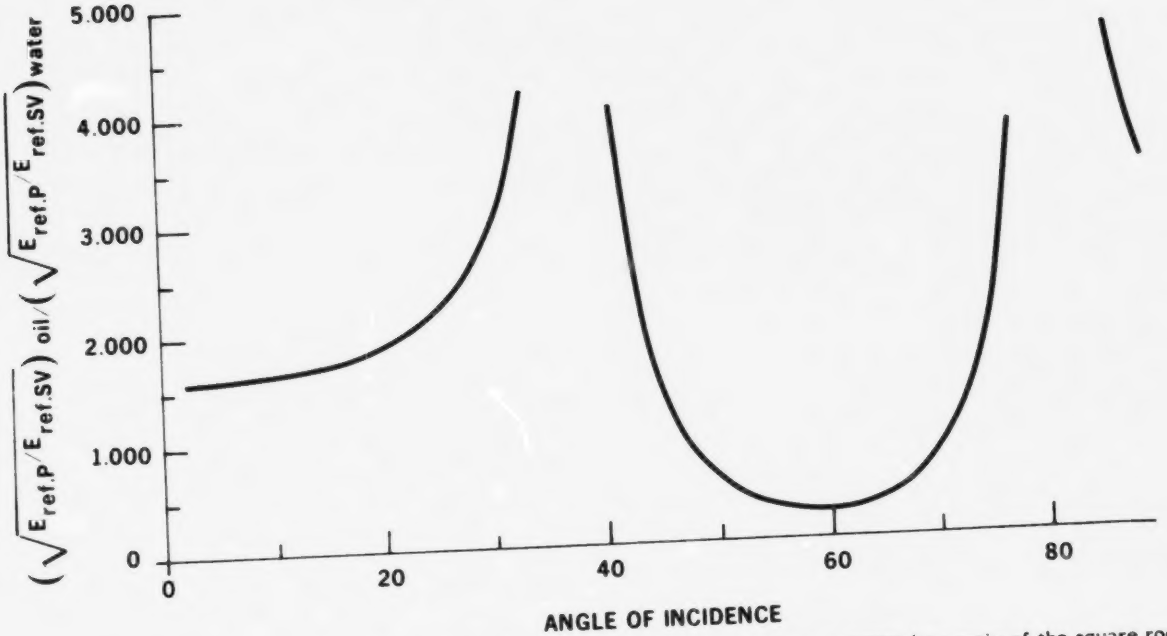

FIGURE 8 P WAVE INCIDENT IN THE SEA ICE AGAINST OIL OR WATER (the ratio of the square root of the energy ratio of the reflected P wave to the SV wave of the ice-oil interface to the ice-water interface vs incident angle. The oil is considered as a solid)

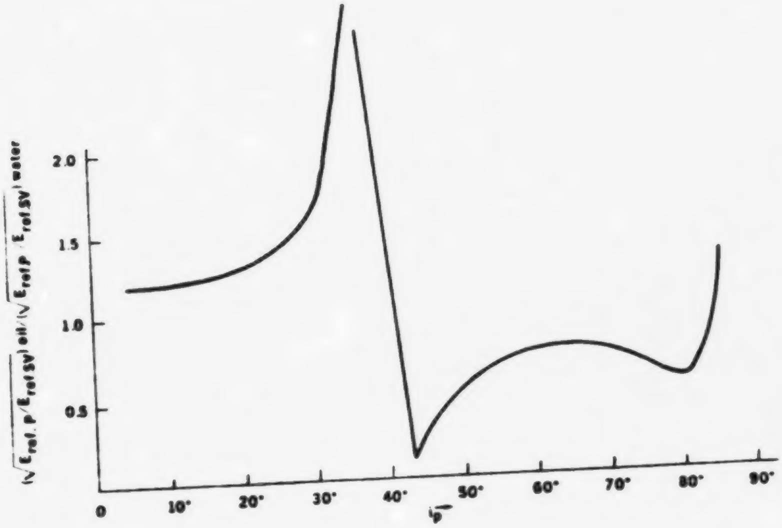

FIGURE 9 P WAVE INCIDENT IN THE SEA ICE AGAINST OIL OR WATER (the ratio of the square root of the energy ratio of the reflected P wave to the SV wave of the ice-oil interface to the ice-water interface vs incident angle)

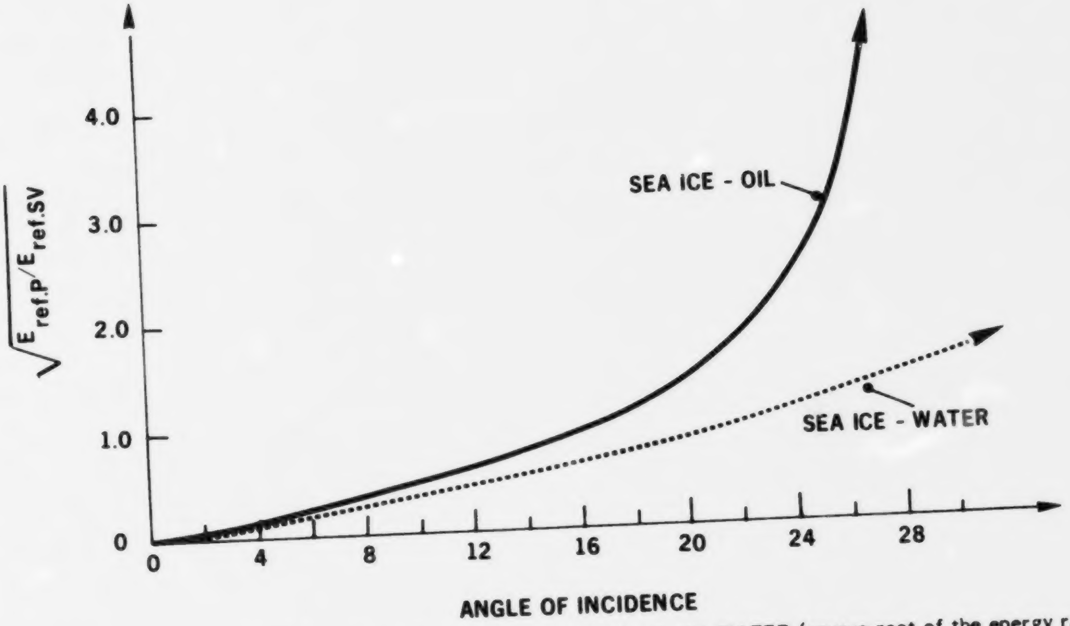

FIGURE 10 S WAVE INCIDENT IN SEA ICE AGAINST OIL OR WATER (square root of the energy ratio of the reflected P wave to the reflected SV wave sv incident angle. The oil is considered as a solid)

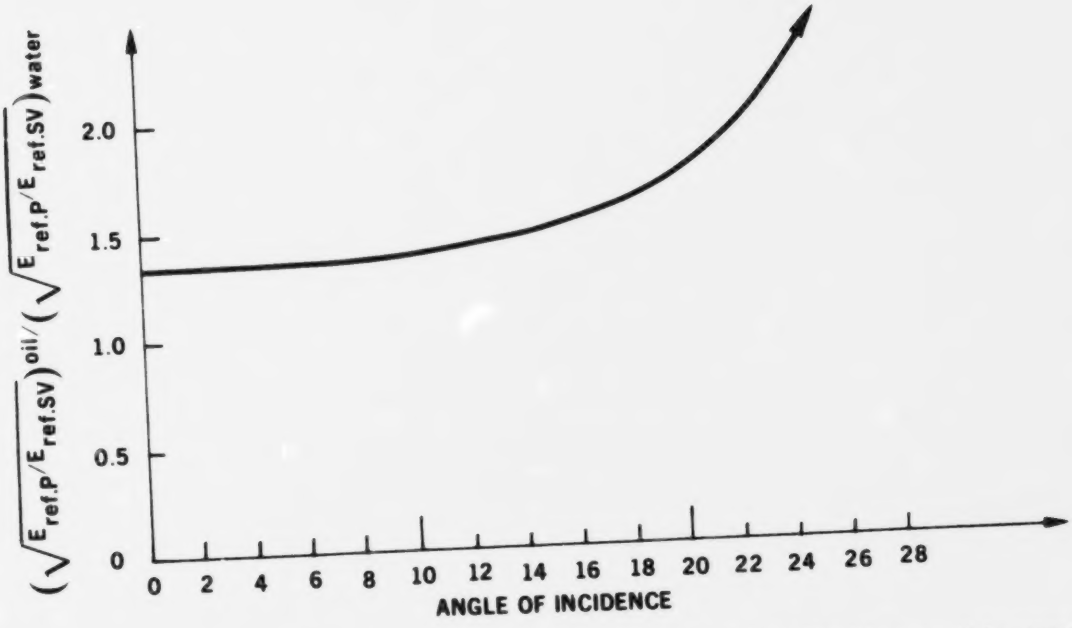

FIGURE 11 S WAVE INCIDENT IN THE SEA ICE AGAINST OIL OR WATER (the ratio of the square root of the energy ratio of the reflected P wave to the SV wave of the ice-oil interface to the ice-water interface vs incident angle. The oil is considered as a solid)

Two requirements need to be satisfied. First, the electrical matching of the transducer to the driver has to be adequate, a point which hardly needs discussion. Second, the acoustical matching of the piezo electric element to the ice has to be sufficient to give a Q value approaching unity. There are many ways of achieving such a match. We chose to use a sandwich transducer in which the plates were aluminium of 1/4 wavelength thickness. As aluminium has an acoustic impedance which is approximately the harmonic mean of ice and piezo electric material, it can be shown that such a design will provide an excellent match to the ice. The performance and design of these transducers are illustrated in Figures 12, 13 and 14.

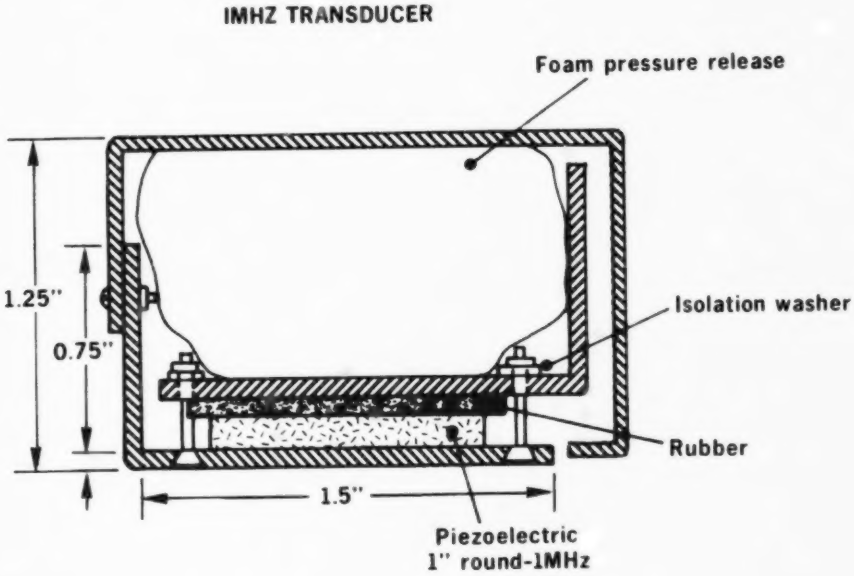
IMHZ TRANSDUCER
Foam pressure release
1.25"
0.75"
Isolation washer
Rubber
1.5"
Piezoelectric
1" round-1MHz

FIGURE 12 1 MHZ TRANSDUCER

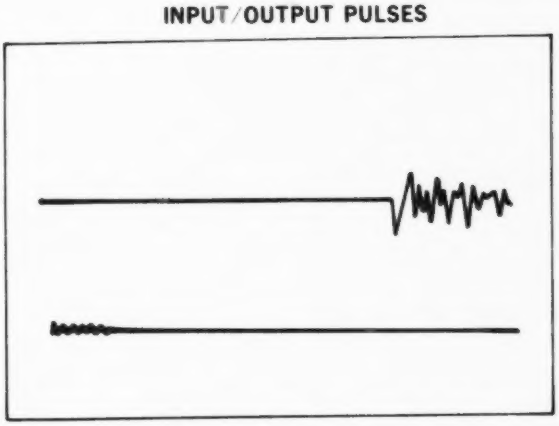

FIGURE 13 INPUT/OUTPUT PULSES

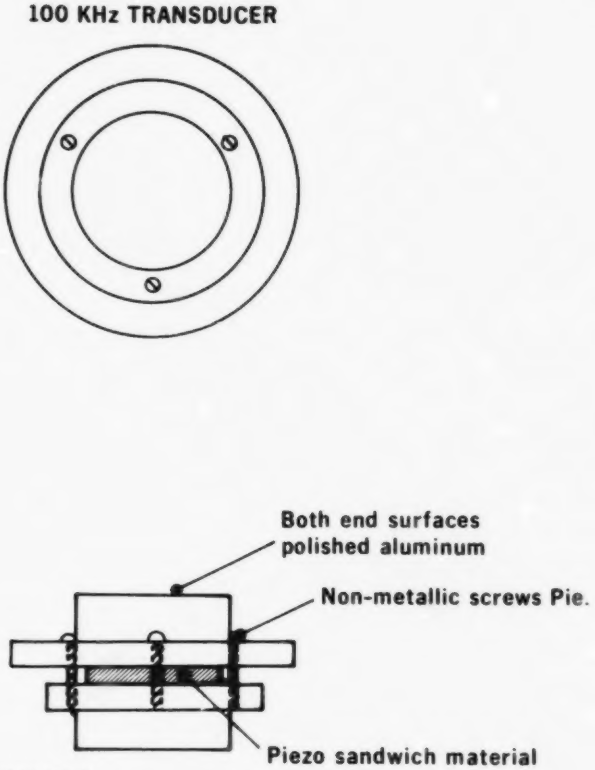

FIGURE 14 100 kHZ TRANSDUCER

## CONCLUSION

The measurement of the visco-elastic properties of crude oil is described; the data have been used to assess the usefulness of shear and compressional ultrasonic waves in the search for trapped oil under ice. Both modes are useful, but it is shown that compressional waves are to be preferred. Detailed evaluation of the effects of the ice/oil and ice/seawater interfaces on incident ultrasonic waves has been presented. It is shown that the effects of the different interfaces produce substantially different return signals. A brief description of the design of ultrasonic transducers for the studies has been given.

## ACKNOWLEDGEMENTS

This work is support by funding from Esso Research Limited and the Environmental Protection Service. The valuable assistance of T. Hayman, Mr. Yeatman and J. Aerts during the study is acknowledged.

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Mason, W.P., W.O. Baker, H.G. McSkimin and J.H. Heiss, "Measurement of Shear Elasticity and Viscosity of Liquids at Ultrasonic Frequencies", Phys. Rev., 75, pp. 936-, (1949).

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# EXPERIMENTS IN THE DETECTION OF OIL-UNDER-ICE USING ACOUSTICS

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Knudsen Engineering Limited
Richmond, Ontario

Recent laboratory and theoretical studies by H. Jones at Dalhousie University have explored the possibility of detecting the presence of oil under sea ice using an active acoustic technique. This work, which is reviewed elsewhere in these proceedings, indicates that it may be possible to distinguish between an ice/oil interface and an ice/water interface on the basis of differences in the relative amplitude of the shear wave generated at the interface by an incident compression wave.

The present project was initiated in late 1982 to carry out a program of hardware development and evaluation in parallel with the research effort. The objective is to produce a "breadboard" oil-under-ice detection system, based on the principles established by the Dalhousie research, which could be used for experiments under actual Arctic conditions.

The project was originally scheduled to begin with a series of field tests to generate some basic test data for design purposes and to evaluate several alternative transducer and circuit configurations. The tests were optimistically scheduled to be carried out in late February 1983 in an outdoor sea ice test basin at ESSO Resources Canada facilities in Calgary. However, these plans were derailed by a serious shortage of ice brought about by the unseasonably warm weather in January and February.

The unexpected cancellation of the field program forced a readjustment of project objectives. A decision was made to proceed with a modified test program using cold room facilities provided by the Environmental Protection Service at their River Road Laboratory in Ottawa, and a small test tank was constructed for this purpose. Unfortunately, because of the delays involved in rearranging the program, no test results are yet available.

The new test facility is a highly artificial environment for studying sea ice, compared to the very much larger outdoor test basin, but it has the advantage of providing a more stable and controllable environment. The revised test program calls for a more thoroughly documented series of tests than would have been possible with the original plan, particularly with respect to the acoustic characteristics of the ice.

The test tank is a cube (1.2 m x 1.2 m x 1.2 m) constructed of plywood with 41 cm square plexiglass windows in all four sides. The inside of the tank is lined on all four walls with styrofoam (except for the windows, or course), which serves the dual function of providing crush space to accommodate expansion of the ice, and of insulating the sides to ensure that the ice grows evenly down from the top. An immersion heater in the tank assists in melting the ice when necessary. A wideband calibrated hydrophone is mounted centrally in the tank to measure the transmitted signal in the water. Provision is made for inserting oil under the ice through a length of plastic tubing.

The cold room in which the test tank is located is capable of maintaining an average temperature of at least -5°C and produces several centimetres of ice in a few days.

From the instrument designer's point of view, the primary requirement of an oil-under-ice detection system based on the principles developed in the Dalhousie research is to reliably and repeatably distinguish between the shear component and the compressional component of the received signal, and so the basic motivation for the present tests is to investigate ways of making this distinction. The most obvious distinguishing feature is the propagation velocity, and thus the time of arrival. Separation of the two components on the basis of their time-of-arrival is primarily a matter of transmitting a sufficiently short acoustic pulse that the two signals do not overlap at the receiver. A substantial portion of the effort will therefore be devoted to selecting the transducer configuration and drive circuitry which offer the best transient performance. The impedance characteristics of each of the transducers will be measured under loaded and unloaded conditions, and every effort will be made to optimize both the mechanical impedance matching to the ice and the electrical impedance matching to the drive circuitry.

Several different configurations of transmit and receive transducers have been constructed for the tests. All of the transducers used to date have been variations of a basic sandwich design using one or two piezoelectric ceramic discs between aluminum plates and are based on a design by Jones. The primary consideration in the transducer design is transient response, as mentioned above. The range of resonant frequencies represented by the transducers constructed for the present series of tests is between 600 kHz and 100 kHz. It is anticipated that a few transducers with frequencies in the 100-150 kHz range will also be assembled.

A capacitive-discharge pulse generator with variable pulse repetition frequency, pulse length, and pulse amplitude has been designed and constructed to provide a repeatable excitation for the transducers. All of the test data will be documented with oscilloscope photographs.

## ACKNOWLEDGEMENTS

This work is supported by funding from ESSO Resources Canada Limited and by the Environmental Protection Service.

## REFERENCES

Jones, H.W. and H.W. Kwan, "The Detection of Oil Spills Under Arctic Ice By Ultrasound", Proc. Fifth AMOP Technical Seminar, pp. 391-411, (1982).

# INVESTIGATING THE PRACTICAL APPLICATION OF THE RESONANT SCATTERING THEORY FOR THE DETECTION OF OIL UNDER SEA ICE

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## INTRODUCTION

This research being performed by Dean Engineering Associates, Ltd. (DEA) for Esso Resources Canada Ltd. (ERCL) and the Environmental Protection Service is based upon the resonant scattering theory (RST), as discussed in the paper "Radar Resonant Reflection from Sets of Plane Dielectric Layers" by P.D. Jackins and G.C. Gaunaurd. The USA CREEL Special Report 81-23 "Electromagnetic Subsurface Measurements", by Dean, provides a review of the impulse radar system being used in this work, and illustrates the characteristics of the material and media of interest.

The field application of the RST has many intriguing prospects for the detection of oil-under-ice. In order to access the utility of the theory, this work addresses two areas needing further investigation: the implementation of a radar/analyzer system to obtain the characteristics of the response surface (see Jackins and Gaunaurd), and the effect actual material properties have on the detection scheme.

Arctic field conditions in which an oil spill has occurred will be modelled in laboratory experiments. An impulse radar system will be used to generate, transmit, receive, and record frequencies over a broad band. A real-time fast-Fourier transform (FFT) spectrum analyzer will transform the time-domain radar data to the frequency-domain data necessary to generate equi-incident angle profiles in the response surface, so that resonant frequencies and resonant half-widths can be measured.

## OBJECTIVE

The study will investigate the practical application of the resonant scattering theory in the field detection of an oil layer between seawater ice and seawater. This investigation is being accomplished by reproducing the field electromagnetic characteristics of the media in a test tank, constructing the response surface obtained by a spectrum analysis of the impulse radar returns from the media, and comparing the test data with the RST predictions.

## DISCUSSION

### Media Properties

Jackins and Gaunaurd assumed that medium 2 (oil) and medium 3 (seawater ice) were dielectric, and that medium 1 (seawater) was nonconductive. In the more general expression, the character of a return from an interface between any media 1 and 2 may be seen in its reflection coefficient, $r_2$:

$$r_2 \quad \alpha \quad \frac{z_1 - z_2}{z_1 + z_2} \quad \alpha \quad \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$

where $z_1$ and $z_2$ are complex characteristic impedances of the media, and $\varepsilon_1$ and $\varepsilon_2$ are complex dielectric permittivity of the media. $\varepsilon_1$ is usually expressed as

$$\varepsilon_i \quad = \quad k_i^* \varepsilon_o,$$

where $k_i^*$ is the complex relative dielectric constant and $\varepsilon_o$ is the dielectric permittivity of free space. Now,

$$k_i^* \quad = \quad k_i' - j\, k_i''$$

where $k'$ is the real part, and $k''$ is the imaginary part. A frequency-dependent conductivity ($\sigma_i$) term adds to the imaginary part, and the result is

$$k^* \quad = \quad k' - j\, k'' - j\, (\sigma_i / \omega \varepsilon_o)$$

$$= \quad k' - j\,(k'' + \sigma_i/\omega\varepsilon_o)$$

and then

$$\varepsilon_i \quad = \quad k'_i\,\varepsilon_o - j\,(k''_i\,\varepsilon_o + \sigma_i/\omega)$$

These (and, therefore, $r_2$) are complex variables, and the return from an interface is a function of the relative magnitudes of these characteristic parameters.

It's important to recognize that sea ice is not a dielectric. The refractive index, $n_3$, for sea ice is mainly determined by

$$n_3^2 \quad = \quad \varepsilon_3 - j\,(\sigma_3/\omega\varepsilon_o)$$

which, at 100 MHz, is

$$n_3^2 \quad = \quad \varepsilon_3 - j\;1.8 \times 10^2\,\sigma_3$$

The conductivity varies with depth, but for the lower portion of a sea ice sheet, a conservative conductivity estimate is 0.02 mhos/m. Then

$$n_3^2 \quad = \quad \varepsilon_3 - j\;3.6.$$

A comparison of the range of $\varepsilon_3$ in CRREL SR 81-23 shows that conductivity is as important as real permittivity for the lower frequencies under consideration. Furthermore, the conductivity of seawater. $\sigma_1$, is certain to be a prominent factor.

These points may be significant, but at this time do not make the application of the RST any less attractive. They do, however, emphasize the need for precise experimental control and media characterization. Measured media values may initiate a data base for further research, and may be used in the generation of a more realistic theoretical version of the response surface.

### Modelling Facility

The seawater tank is schematically shown in Figure 1. As an ice sheet is grown (naturally or with cooling panels), the water is recirculated, monitored, and kept at the appropriate salinity. Such a tank is shown in Figure 2 with its insulated cooling panels lifted. Figure 3 shows the recirculation pump and valving, and Figure 4 shows an example of the ice grown. With proper freezing rate and water salinity control, the salinity profile in multi-year and first year ice can be modelled. Conventional manual, hot-wire, ultrasonic and impulse radar techniques will be used to contour the ice sheet. The oil thickness will be determined from a knowledge of the bottom ice contours and the inserted oil volume, and will be verified periodically by a diver. The structure and electrical characteristics of the ice will be obtained when testing of a sheet is complete.

### Instrumentation and Technique

The impulse radar system emits wavelets whose complete reflection ($R \approx -1$) is similar to that shown in Figure 5. The transform of that wavelet yields the curve of Figure 6. An inspection of wavelets from higher-frequency antennas resently available indicates a coverage of the spectrum up through 4-5 GHz with attenuation less than 40 dB.

The power spectrum of the complete reflection will be subtracted from the power spectrum of the radar return from an interface, in order to compensate for the variations in transmitted power across the frequency bands. The resultant response surface profile should then display those undulations caused by the resonances predicted with the RST.

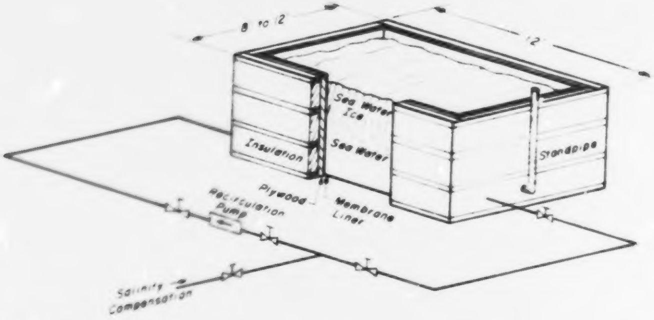

8' to 12'
12'
Sea Water Ice
Sea Water
Insulation
Standpipe
Plywood
Membrane Liner
Recirculation Pump
Salinity Compensation

FIGURE 1 FUNCTIONAL SCHEMATIC OF SEA ICE TEST TANK. View ports and underwater lighting can be used in this configuration. Freezing can be done by heat transfer panels on the surface, or by blowing refrigerated air across the top.

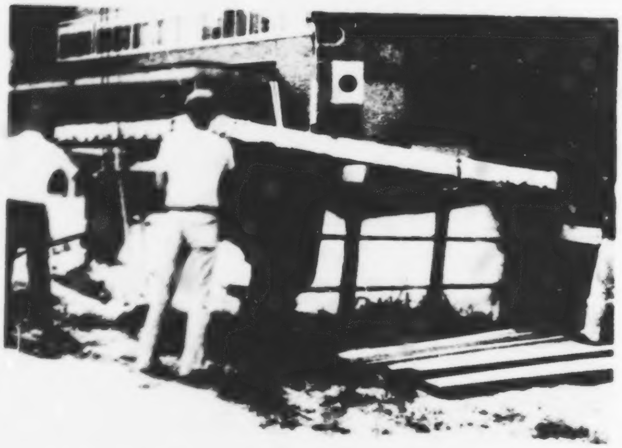


FIGURE 2 2.4 M x 2.4 M SEAWATER TEST TANK WITH (TOP-INSULATED) COOLING PANELS BEING LIFTED OFF THE SURFACE

FIGURE 3 PUMP AND VALVE ARRANGEMENT FOR THE TEST TANK OF FIGURE 2

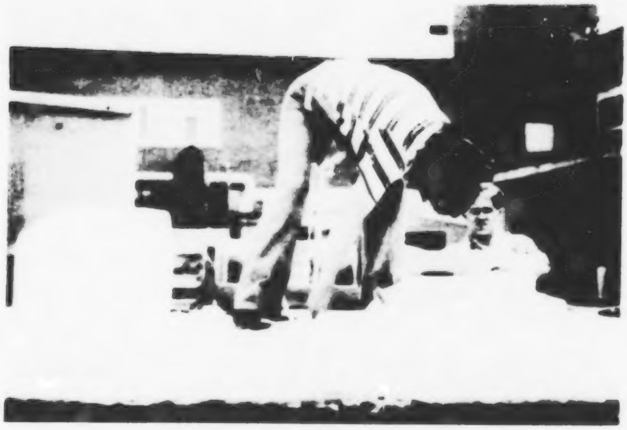


FIGURE 4 SAMPLE ICE BLOCK BROUGHT UP ON THE TOP OF THE ICE SHEET IN THE TEST TANK OF FIGURE 2

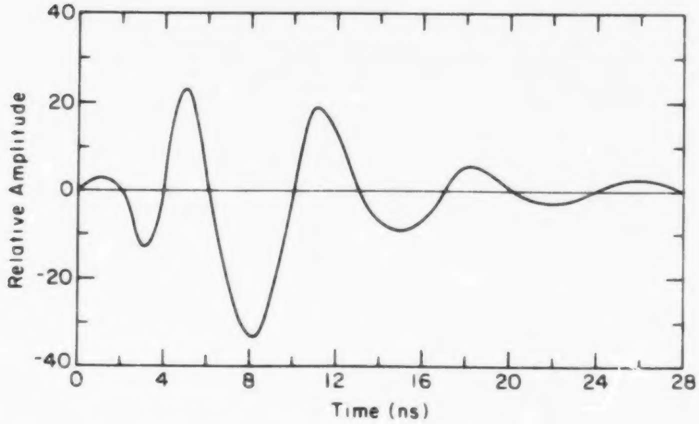


FIGURE 5 REFLECTED (R=-1) WAVELET TYPICAL OF THE BOW-TIE IMPULSE RADAR ANTENNA

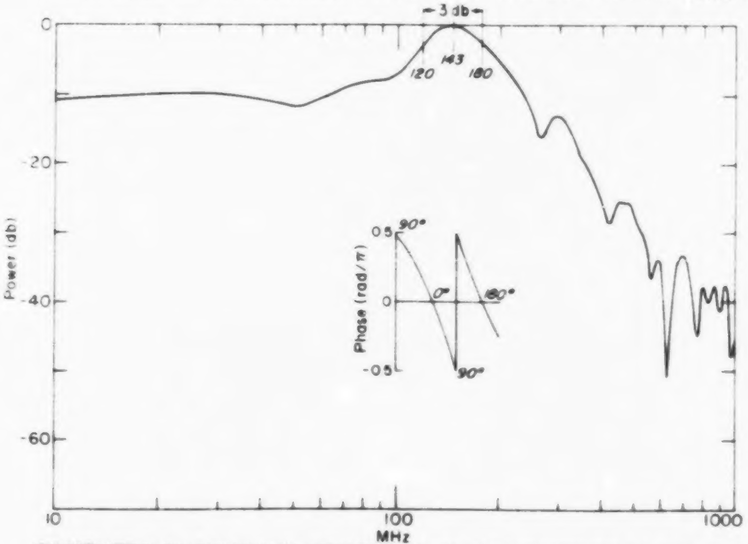


FIGURE 6 COMPUTED FREQUENCY SPECTRUM OF THE WAVELET IN FIGURE 5. The center frequence is 143 MHz, 120 and 180 MHz being the 1/2 power points. The wavelet spectrum is a characteristic of the particular antenna used.

Spectrum analysis will be done with the Hewlett Packard (HP) Model 3582A, HP Model 5420A, and/or the Nicolet Scientific Corporation (NSC) Model 446B. This equipment provides a sensitivity from 65 to 100 dB, a frequency resolution of 0.01 Hz, and has a compatible bandwidth with the recorded GSSI radar data.

Figure 7 is an example of the FFT computations performed on actual radar returns from a complex media, but illustrates the kind of equi-incidence angle profile of the response surface which we anticipate. The abscissa frequency range is scaled down from about 1.6 GHz.

The waveform averaging capability of these instruments is presumed adequate to reduce the background system noise to an acceptable level. If this proves to be incorrect, more precise transform calculations may be made on the time-domain data with a general-purpose computer.

Although Jackins and Gaunaurd assume that the media are in the far-field of the radar beam, we feel that an analogous interferometric relationship may exist in the near-field as well. The coupling advantages of operating in the near-field, especially in consideration of the attenuation of some sea ice forms, warrant conducting parallel testing in that mode. These tests are scheduled along with the far-field tests.

The success of this technique has significant applications. With minor modifications, there will immediately exist a fieldable system (albeit not real-time) which can be used in the detection of oil under sea ice. Media characterization can be made from the relative reflection amplitudes over the frequency bands and from the phase information implicit in the radar return. The amplitude measurements (and, therefore, the profiles of the response surface) will be made. The phase information will be available in the recorded data, but its investigation and comparison with the calculated phase change are not considered to be within the scope of this present work.

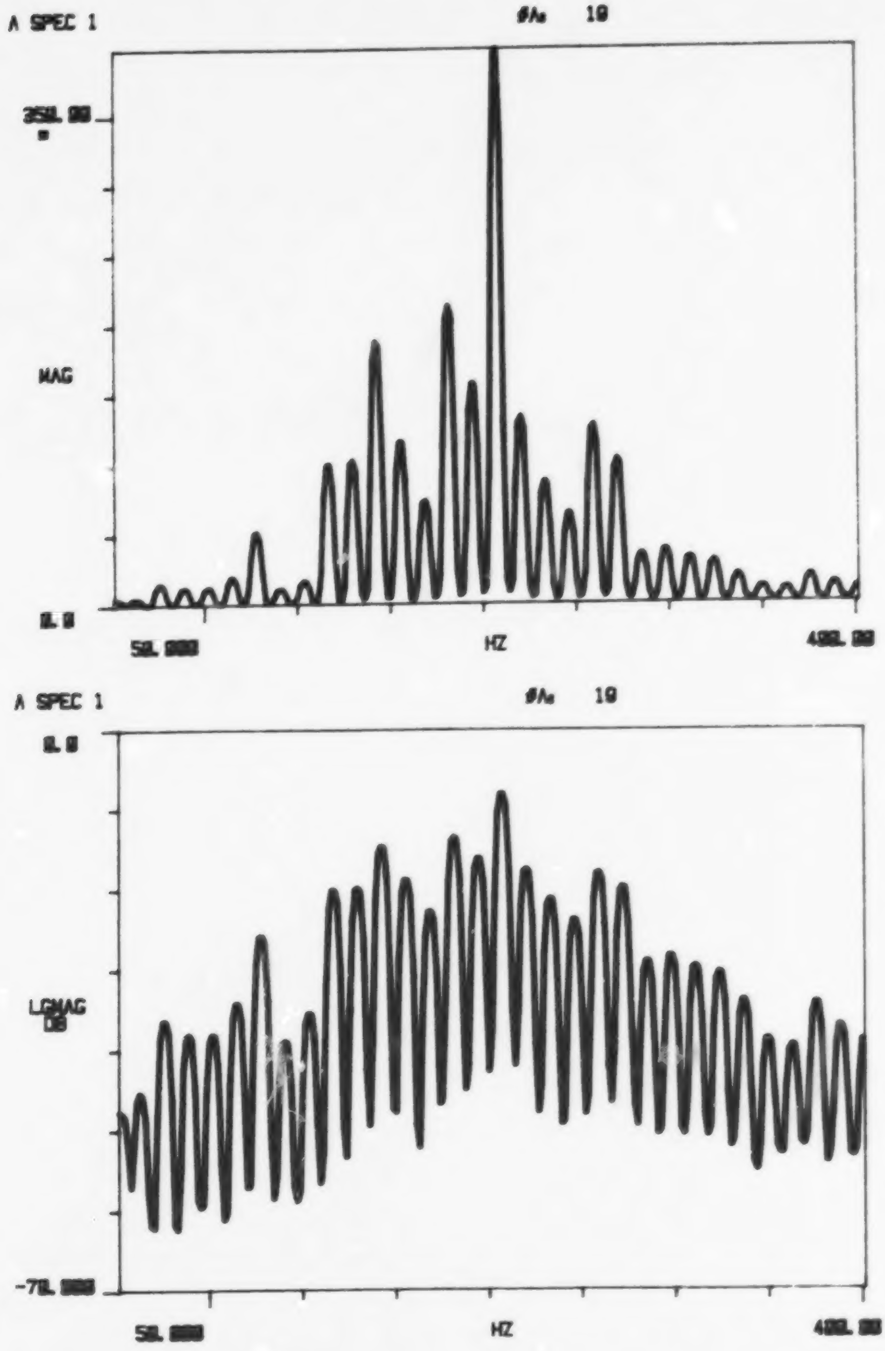


FIGURE 7 EXAMPLES OF THE POWER SPECTRUM COMPUTED BY AN FFT ANALYZER ON AN ACTUAL RADAR RETURN FROM A COMPLEX MEDIA INDICATING SIMILAR MODULATION CHARACTERISTICS TO THOSE SOUGHT BY THE PRESENT PROGRAM

# SESSION VI ACTIVITY UPDATES

## FOUR YEARS OF ACTIVITY TO IMPROVE NORWAY'S ABILITY TO CLEAN UP OIL POLLUTION, 1979-1983

J.N. Langfeldt
PFO
Oslo, Norway

### INTRODUCTION

Since 1979, Norway has carried out an Oil Pollution Control - Research and Development Program (PFO). The effort was aimed at developing methods and equipment to increase the ability to clean up oil pollution resulting from large accidental oil spills. After the 4-year program ends, it will be decided if further activity is needed. PFO presented all results obtained at a conference held in May, 1983; the activity started in 1979 will be finished by the end of June, 1983. However, it has already been decided to extend the research and development effort in Norway for at least another 2 or 3 years; PFO will thus live on.

PFO is a government-sponsored activity. Most of the funding has been from the government; about 15% has been from the offshore oil industry. In the future, the oil industry will probably finance a larger part of the activity. The work has been aimed at fulfilling the aims initially put forward by the Norwegian Ministry of Environment after discussions with the oil industry. However, PFO has made certain changes in the priorities. In some areas of research and development, it has been recommended to continue work in order to give full effect to the work done by PFO. However, all the results need to be followed up by the responsible authorities to be of any use in the combat against oil pollution in Norway.

In order to fulfill these aims, PFO has especially worked with:

a) trial with full-scale mechanical and chemical oil cleanup equipment and methods on the ocean with oil present;

b) development of an ocean-going skimmer (oil trawl) with high capacity (400 $m^3$ oil/h);

c) research into separation of oil/water on skimming vessels;

d) research into new technology to pick up oil from underwater blowouts;

e) development of new mechanical equipment for shore cleanup of oil;

f) development of a transportation system for oily debris picked up in areas difficult to reach;

g) development of methods to treat oily debris;

h) development of ways to lessen oil leakage from wrecked tankers;

i) development of ways to fight oil pollution in sheltered waters along the coast;

j) development of an analytical tool for planning oil pollution combat;

k) development of an analytical tool to access cost/benefit of oil pollution on local and national levels.

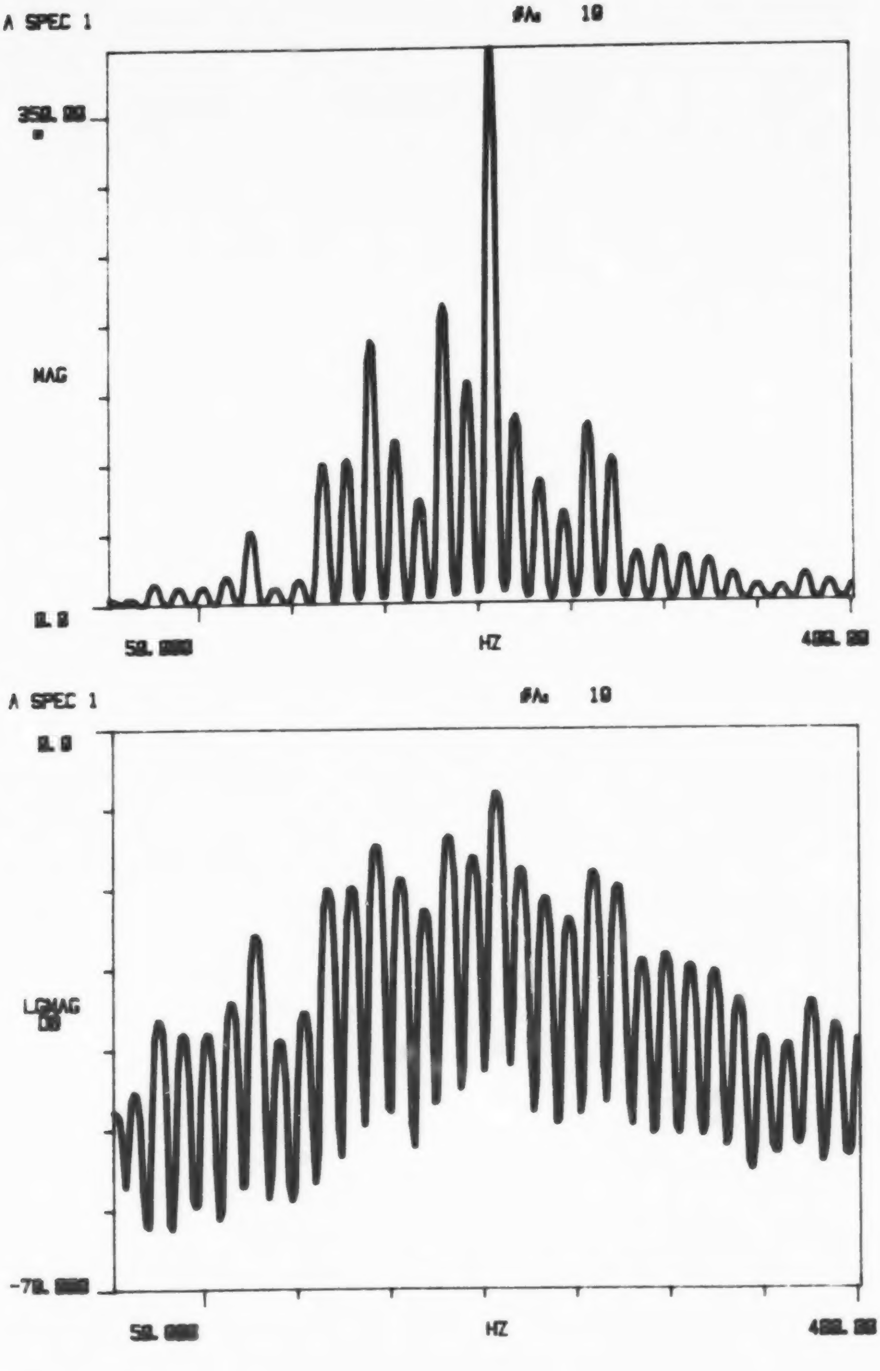
One of the main conclusions to be drawn from the projects and from international contracts during this 4-year period is that no matter what we do to fight oil pollution on the sea, some of it will always end up on shore. The work done after PFO must aim to tackle the problem of shore cleaning and further treatment of oil; more effort must be expended than that provided by PFO.

### THE PURPOSE AND STRATEGY OF PFO

The purpose of PFO was to find methods and equipment that would lessen the environmental damage resulting from oil pollution. Oil pollution, in this context is accidental spills from offshore activities or from ship traffic along the coast. The strategy to reach this aim was formulated as follows:

a) PFO should take the initiative and contract out research to obtain the knowledge necessary to make oil pollution combat more efficient;

b) determine areas where development was necessary to get better oil cleanup equipment, and then give support to this development;



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a) PFO should take the initiative and contract out research to obtain the knowledge necessary to make oil pollution combat more efficient;

b) determine areas where development was necessary to get better oil cleanup equipment, and then give support to this development;

c) from the results of a) and b), and on the basis of other theoretical and practical knowledge, the possibilities and difficulties associated with fighting oil pollution should be clarified;

d) the cost associated with different methods to fight oil pollution should be determined;

e) from the results of c) and d), the responsible bodies should be given a better foundation when choosing aims and strategies to fight oil pollution;

f) give the government and others information on the results of the projects;

g) increase the general level of know-how related to oil pollution in Norwegian research and industry.

This purpose assumes that it is possible to make oil cleanup more efficient. It does not, however, say by how much. To meet this requirement, PFO wanted to support anything that would result in a marked increase in our ability to fight oil pollution.

It should be noted that only fighting oil pollution is discussed here. Another research program in Norway evaluates damage to marine life due to oil pollution and methods used to fight it. There is also a research program to increase the safety of offshore drilling generally.

### Some Results from the PFO Activity

Altogether, 70 research and 8 development projects have been completed since the start of 1979. About 40 mill. NOK have been spent ($1 U.S. = 7,15 NOK). The projects include areas such as:

a) aging of oil;

b) emulsification/de-emulsification;

c) drifting and spreading of oil on the ocean and in bays (fjords);

d) natural dispersion due to wave action;

e) trials of full-scale mechanical equipment with oil offshore Norway (the first in Norway);

f) development of two high-capacity, ocean-going skimming equipments (400 $m^3$/h);

g) development of two one-boat skimming systems with a capacity of about 100 $m^3$/h;

h) laboratory and field experiments on efficiency and toxicity of oil dispersants;

i) investigation of the possibility to combat subsea blowouts;

j) biological treatment of oil and oily debris in situ and after cleanup;

k) transportation of oily debris from a shoreline with difficult accessability;

l) development of protective clothing for people engaged in oil cleanup;

m) development of a gelling agent for seawater to be spread on the shoreline (under and above water) for protection against oil threatening the shore;

n) methods to separate oil and water;

o) development of ways to decrease the oil leakage from wrecked tankers;

p) studies of the cost and damage of historical spills;

q) development of an analytical tool to access the cost/benefit of different organizations and methods to fight oil pollution.

As part of this work, several workshops have been held, some with international attendance. The purpose of this has been both to obtain and spread information, and plan further research and development. We believe that this effort has increased the understanding of how oil pollution can be attacked. Of most importance is the recognition that it has to be expected that oil pollution will occur and will come ashore. This is not a result of PFO alone, but rather something that has developed over time on the basis of international contacts, and was reinforced by the results from PFO.

# SESSION VII EXPERIMENTAL SPILLS

## FATE AND BEHAVIOUR OF WATER-IN-OIL EMULSIONS IN ICE

I.A. Buist, S.G. Potter
Dome Petroleum Limited
Calgary, Alberta

D.F. Dickins
D.F. Dickins Associates Ltd.
Vancouver, B.C.

### INTRODUCTION

Observations of the 1979 Ixtoc oil well blowout in the Gulf of Mexico indicated that a stable water-in-oil emulsion was formed. Although the mechanisms of emulsion formation are not well known, it is known that several Beaufort Sea oils (for example Kopanoar) form extremely stable emulsions. Thus, the potential exists for the presence of emulsions should a blowout occur in the Beaufort Sea.

Previous experiments have considered the fate of crude oil discharged under first year sea ice (NORCOR, 1975; Dome, 1981). Crude oil was found to be quickly encapsulated in the growing ice sheet, where it remained relatively unchanged throughout the winter. It rose through the natural brine channel network as the sea ice was warmed in June. Exposed on the ice surface in pools, the oil was then burned in situ prior to breakup of the ice sheet.

The occurrence of stable water-in-oil emulsions could drastically alter past conclusions regarding the fate and behaviour of oil spills under sea ice. A major concern was that emulsions, having viscosities which are orders of magnitude greater than those of crude oil, would not flow upward through the brine channels. Hence, the oil may not appear on the surface until it is too late to mount an effective in situ burning operation. Other theories, similarly untested in the field, predicted that water-in-oil emulsions could break when frozen due to internal ice growth.

This field experiment was designed to determine the actual behaviour, fate, and cleanup effectiveness when stable water-in-oil emulsions are spilled under first year sea ice. The experiment was deliberately biased in that an extremely well mixed and stable emulsion was placed under sea ice in late winter. The ice was of a thickness such that the sheet would break up in spring prior to the emulsion being exposed by ablation alone. If this emulsion appeared prior to breakup and was amenable to cleanup by in situ burning, then emulsions formed by a subsea blowout under ice, or by any other mechanism, at any prior time would certainly appear and be burnable.

### EXPERIMENTAL DESIGN

#### Site Location

The major criteria for the test site were firstly, that it be in the landfast ice zone without significant ice pileup or rubble; secondly, that the water depth be no less than 4.5 m to permit diving operations; and thirdly, that it be readily accessible and close to logistic support. For these reasons, a site was chosen near Dome's McKinley Bay operation (Figure 1). The location was approximately 100 m north of the artificial protection island, safely removed from any vessel movements, in an area with water depths in the range of 4.4 to 5 m.

#### Site Preparation

In order to contain the planned oil discharges, six fabrene skirts were installed at the test site in November, 1981. Chain saw slots were cut in the 52 cm ice and the skirts inserted to form six circular test areas each 5 m in diameter (Figure 2). The skirts were weighted along the bottom, and were fabricated 2 m high so that about 40 cm of curtain would hang below the ice in March. A foam collar was threaded through the top of each skirt to provide flotation during installation and ensure oil containment in spring. As the temperature at the time of installation was -25°C, the skirts were quickly frozen into the growing ice sheet. Cut ice was transported well clear of each test area to avoid unrepresentative snow drift.

The test areas were situated on corners of a triangle approximately 100 m on a side (Figure 3). To assist with the subsequent diving operations, a series of weighted guide ropes were installed along lines leading from the centre of the triangle to each skirt.

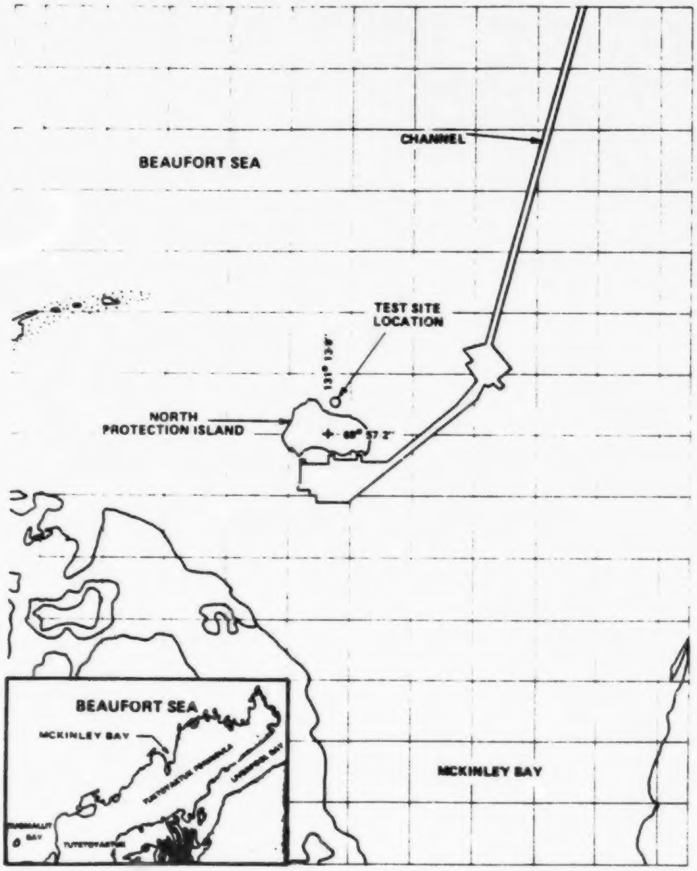
CHANNEL
BEAUFORT SEA
TEST SITE LOCATION
131° 13.8'
NORTH PROTECTION ISLAND
69° 57.2'
MCKINLEY BAY
BEAUFORT SEA
MCKINLEY BAY
BAY

FIGURE 1 TEST SITE LOCATION

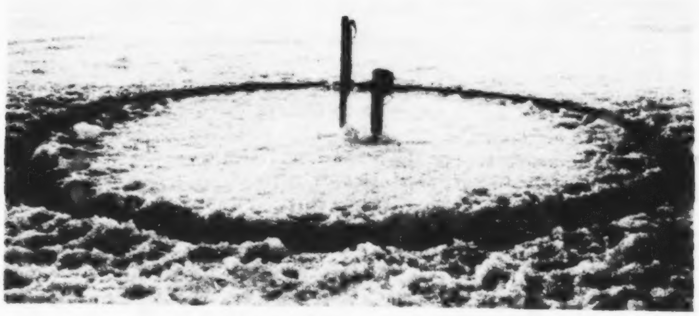

FIGURE 2 INSTALLED SKIRT, NOVEMBER 1981

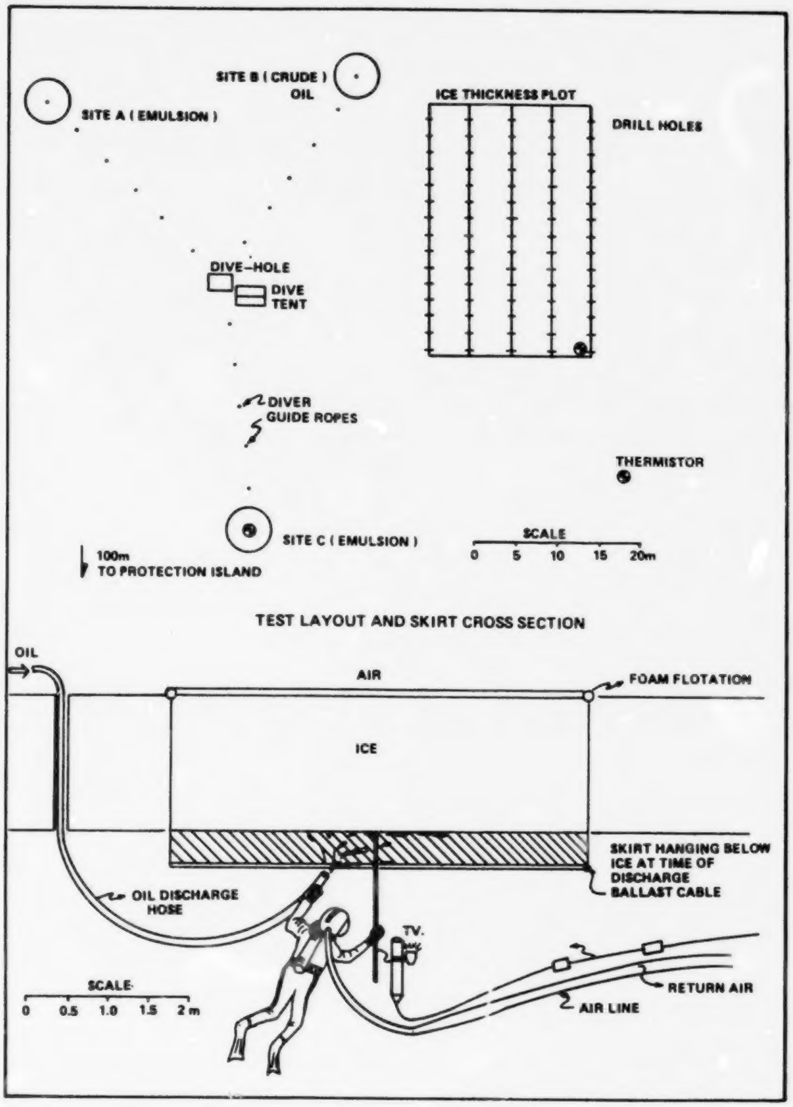
SITE B (CRUDE) OIL
SITE A (EMULSION)
ICE THICKNESS PLOT
DRILL HOLES
DIVE-HOLE
DIVE TENT
DIVER GUIDE ROPES
THERMISTOR
SITE C (EMULSION)
SCALE
0 5 10 15 20m
100m TO PROTECTION ISLAND
TEST LAYOUT AND SKIRT CROSS SECTION
OIL
AIR
FOAM FLOTATION
ICE
SKIRT HANGING BELOW ICE AT TIME OF DISCHARGE
BALLAST CABLE
OIL DISCHARGE HOSE
T.V.
RETURN AIR
AIR LINE
SCALE
0 0.5 1.0 1.5 2 m

FIGURE 3 TEST SITE LAYOUT AND SKIRT CROSS-SECTION

## Oil Discharges

Two test periods were planned: one in early February with an ice thickness of about 120 cm, and a second in late March under 160 cm of ice. Due to delays in receipt of a necessary permit, only the March discharges were completed. Three separate discharges took place between March 20 and 21, two of 60% water-in-oil emulsion, and one of Kopanoar crude oil as a control. Discharge volume was 192 L (1.2 bbl) for each test, selected on the basis of a uniform 10 mm layer over the entire 20 $m^2$ area contained by each skirt.

On March 19, 1982, a large divehole was cut in 165 cm of ice at the centre of the test area established in November. A dive tent was erected alongside the hole to house underwater video and communications equipment. Divers used a surface air supply with a special return air line to avoid depositing large volumes of exhausted air within the test areas. Using the guide ropes installed in November, the divers were able to make their way to and from each test skirt, a distance of 30 m.

An oil/water mixing system consisting of an open drum, piping, circulation and discharge pumps was contained within a plywood hut mounted on a portable sled which would easily towed from site to site. Prior to being discharged, each emulsion (consisting of 114 L water and 78 L oil (59:41)) was recirculated for about 3 hours at 15°C through a high-speed centrifugal pump.

Each skirt was inspected by the diver with an underwater TV system to document all three skirts prior to any oil discharge. One skirt had two segments which had been buoyed up by an accumulation of ice crystals attached to the fabric. Within these areas, representing about 10% of the test area periphery, only 2 cm of skirt was left protruding below the ice. The rest of the fabric all hung below the ice to a minimum distance of 30 cm.

Once the emulsion or crude oil had reached a temperature of 5 to 10°C, a hole was drilled just outside the skirt and a 2.5 cm rubber discharge hose was inserted through the ice for the diver to receive. With the video camera adjusted to observe the oil, the discharge pump was started. The diver then moved the discharge hose gradually around inside the skirt to produce a relatively uniform oil coating of the ice. Flow rates ranged from 12 to 20 L/min; each discharge therefore took 10 to 15 minutes. Video inspections and still photography were carried out under each site 15 min, 6 h and 42-48 h after the discharge had been completed.

### Environmental Documentation and Monitoring

**Ice.** Ice thickness and snow depths were measured (see Figure 3) along a series of lines at a 2 m spacing in November and March to determine the magnitude of under-ice topography that could act to contain oil spilled in a more natural, unconfined state. Cores were also obtained in November and March to document ice salinity for comparisons with previous oil/ice interaction experiments.

Three thermistor chains containing 11 beads each (three in the snow or air, eight in the ice or water) were installed through the ice in November, mounted on 5 cm x 10 cm posts. Two of these chains acted as controls well removed from the spill sites, and one was located at the centre of the skirt ear-marked for an emulsion discharge (Figure 3). These chains were monitored during the March discharges, and again during spring from June 15 until they melted out (about July 1). Water temperature data was extracted and plotted separately. Air temperature readings 1 m above the ice were compared with McKinley Bay drillships records during June and July. From June 15 to July 7, ice ablation was determined by measuring the steady increase in skirt freeboard.

**Oil Fate.** During the spring phase of the program, daily site visits were made between June 15 and site breakup. Observations were made of surface conditions at each site according to the volume of slicks, visible oil migration processes, oil appearance, and ice deterioration. Three time-lapse 8 mm movie cameras were maintained to provide continuous documentation of each test area from June 19 to July 7. This information was combined to produce a comparative plot of oil percent appearance versus time.

**Sampling.** During the March phase, samples of emulsion and straight oil were collected prior to each discharge, and from beneath the ice after 24 hours (emulsion only). A further series of oil samples were collected during the spring phase. Methods included spooning directly from the surface slick into a bottle, coring through to the encapsulated emulsion, and scraping within the original oil layer through holes rotted through the ice. All samples were shipped to Seakem Oceanography Ltd. to analyze the following: density; viscosity; pour point; flash and fire points; gas chromatography; solubility behaviour; and evaporation rates.

## ENVIRONMENTAL CONDITIONS

Environmental conditions affecting the outcome of this project naturally centre around the principal characteristics of the ice sheet itself: growth and melt. Figure 4 shows ice growth curves for McKinley Bay during 1979/80 and 1981/82 compared to a "normal" curve derived from Cape Parry historical records. This plot shows that from January 1, McKinley Bay ice growth during the winter of 1981/82 almost exactly matched the long-term normal statistics.

Salinity profiles measured in November, 1981, and March, 1982, were compared to the previous McKinley Bay oil spill in 1979/80 and characteristic curves for typical sea ice (Weeks and Assur, 1967). Within the error bounds associated with averaging over the sample length and different instruments used, all profiles agree within about one part per thousand. Under-ice roughness is of interest as an indicator of maximum attainable oil pool depth which could build with a semicontinuous source such as an under-ice blowout. Two lines profiled 40 days apart in February and March were plotted for comparison. There was no apparent correlation between the relative shape of the under-ice profiles in February and March. The increased snow depth from 11 cm to 17 cm is accompanied by slightly greater under-ice variations (standard deviation from 1 to 3 cm). Typically, under-ice slopes are about 1 cm over 1 m horizontal distance, so it is not surprising that divers report the ice as appearing absolutely flat.

As shown in Figure 4, ice ablation in 1982 commenced about June 12, approximately 5 days later than the 1980 ice sheet. Figure 5 compares average ice ablation for all sites between the 2 years. Associated environmental data are presented in Figure 6. Ice ablation was late starting in 1982 due to the below-normal temperatures, with limited thawing conditions until June 20. Thereafter, temperatures averaged slightly above normal and resulted in a sharply increased ablation rate from 2.5 to 6.5 cm/day. This is in direct contrast to the 1980 melt when unusually warm temperatures in early June promoted an initial ablation rate of 6 cm/day. This subsequently reduced to 4.5 cm/day after June 20 in response to a cooler second half of June. Breakup of the ice sheet in 1982 occurred within 48 hours of the 1980 experiment, but ice thickness remaining at the time the ice started to move was about 30 cm greater than in 1980.

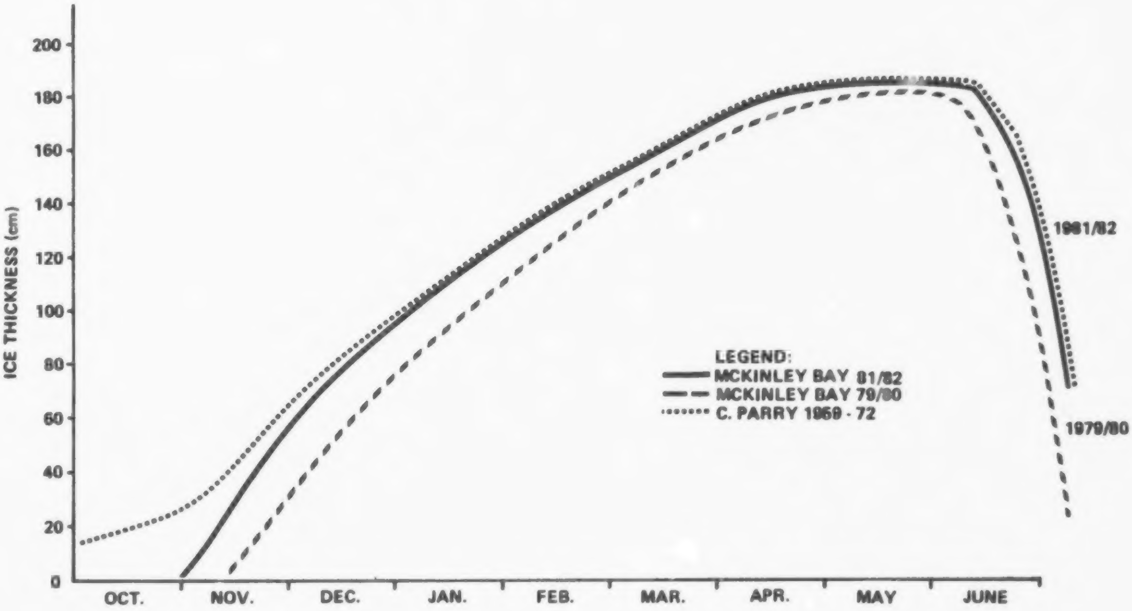

FIGURE 4 COMPARISON OF ICE GROWTH CURVES

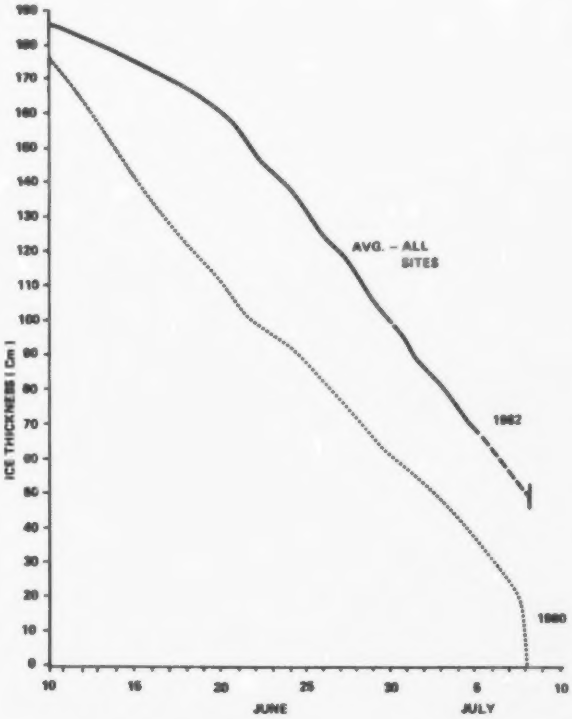

FIGURE 5 ICE ABLATION AT TEST SITES

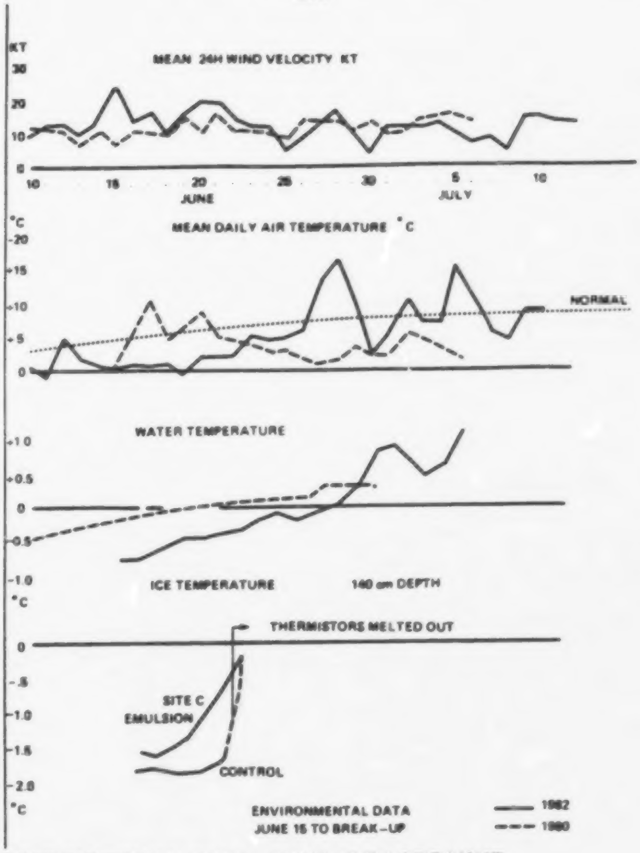

FIGURE 6 ENVIRONMENTAL DATA: JUNE 15 TO BREAKUP

A detailed plot of ablation by site showed no significant differences between the emulsion or crude oil spills (approximately = 10 cm). As noted in 1980, the presence of significant quantities of oil on the surface did not lead to accelerated ablation and, in fact, tended to shelter the ice from direct radiation. Changes in the spring surface appearance of the test sites are discussed in more detail below.

## OIL BEHAVIOUR AND FATE

### Discharge and Encapsulation

Three discharges took place between 1145, March 20 and 1100, March 21. Oil release and subsequent behaviour on floating up against the ice under-surface within the skirt was viewed by colour video link. All discharges were characterized by the following general observations:

a) oil (emulsion and crude) broke onto discrete globules within 15.3 cm of the hose end;

b) these individual viscous globules floated slowly up against the ice and remained at the point of contact, with a distinctly irregular shape;

c) spreading laterally from the point of first contact was negligible for the emulsions and less than 61 cm for crude oil;

d) on completion of the discharge, the emulsion distribution remained static, with an irregular, "lumpy" texture; many highly viscous projections and globules of emulsion were visible, resulting in a rather grotesque appearance.

The crude oil adopted a somewhat more uniform coating than the emulsion, as would be expected from the significant viscosity differences (26 vs 184 cSt @ 10°C - Ref. Seakem Oceanography, May 31, 1982, Appendix C). The actual physical appearance of the oil at various times following discharge is best shown in Figures 7 and 8.

FIGURE 7 SITE A IMMEDIATELY FOLLOWING EMULSION DISCHARGE (WOOD MARKER IS 5 X 5 CM FOR SCALE)

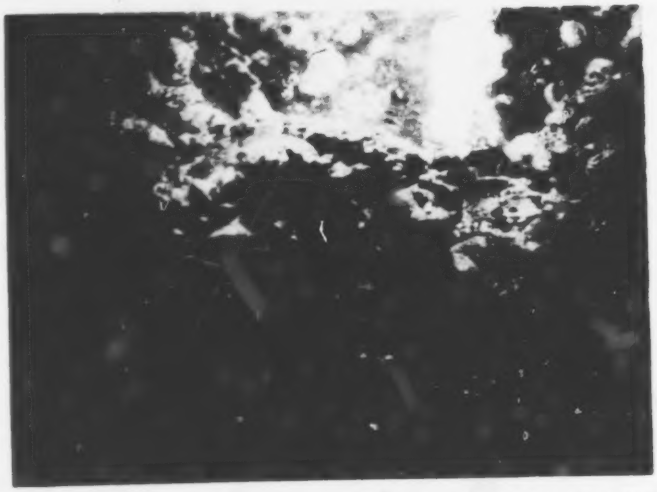

FIGURE 8 SITE A 48 H AFTER DISCHARGE. MOST OF THE EMULSION IS ENCAPSULATED BEHIND 3 MM OF NEW ICE GROWTH

Within 24 hours of discharge, new ice crystals were observed forming within the emulsion itself. By 48 hours, both the emulsion and crude oil were almost completely incorporated within a thin skim of 2 to 3 mm new ice growing beneath the oil. The visual appearance and colour of the oil did not change during this incorporation process.

Cores extracted in June showed that about 20 cm of new ice growth took place beneath the oil layer following discharge. Natural ice growth curves shown in Figure 4 show a similar increase over the same period. These results agree with previous detailed studies in showing that the presence of oil layers within the ice has no measurable effect on the maximum ice thickness reached (NORCOR, 1975; Dome, 1981).

### Spring Conditions

At the beginning of the spring observations on June 15, 1982, all sites were covered by 10 to 20 cm of water. Ice ablation had just started, with about 10 cm of the skirt exposed. Figures 9 through 12 show changes in appearance of test sites A (emulsion) and B (crude oil) between June 15 and July 17, just prior to burning. Figure 13 shows a close-up view of oil migrating and on the surface of Site A. At this site, large quantities of emulsion remained trapped in rotten ice up to July 5. Emulsions floating on the water surface appeared almost identical in physical properties and colour to those viewed under the ice by video camera after discharge (Figures 7 and 8). Field observations were recorded daily for the period June 15 to July 8.

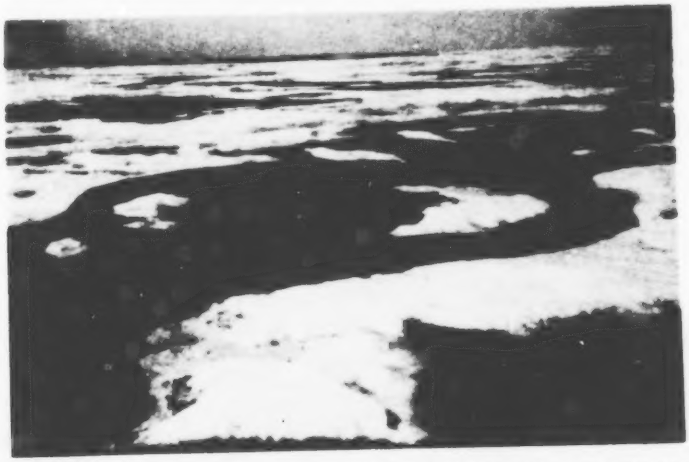

FIGURE 9 SITE A, JUNE 20, 1982 (NOTE SIGNIFICANT MELT; ICE THICKNESS = 150 CM; LESS THAN 5% OIL ON SURFACE)

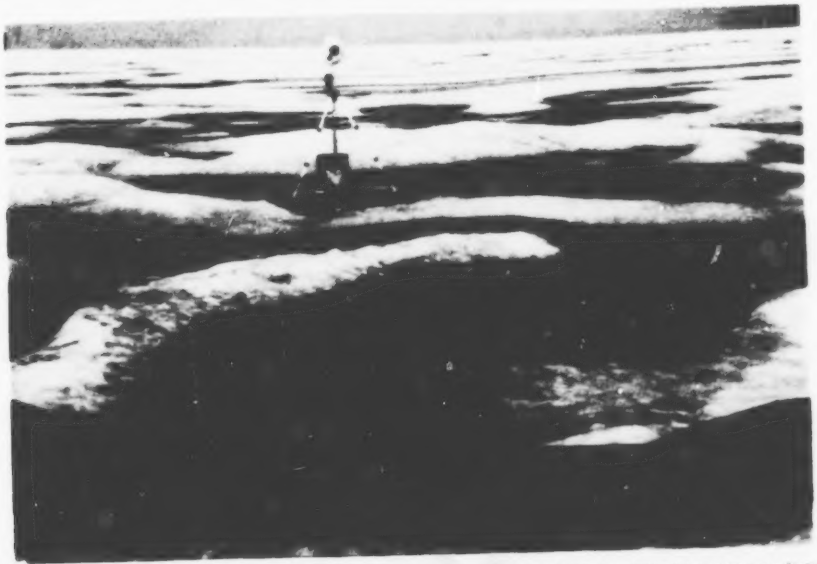

FIGURE 10 SITE A, JULY 3, 1982, SHOWING TIME-LAPSE CAMERA INSTALLATION (ICE THICKNESS = 70 CM; OIL ON SURFACE IS 10% OF ORIGINAL VOLUME)

**Relative Rates of Oil Appearance**

Estimates of oiled area coverage have been combined with a linear increase in slick thickness with time (from 1 mm on first date of significant oiling (10% by area) to July 7 and 8, marking the end of the natural oil migration process and the start of burning). Maximum thickness of oil was taken as 10 mm at Sites A and C, and 7 mm at Site B (corresponding to July 6/7 field observations). It is recognized that any measurements of oil slick thickness are extremely subjective, particularly when such high viscosities are present. The final amount of oil on the surface was calculated by adding the volumes of oil burnt and sorbed.

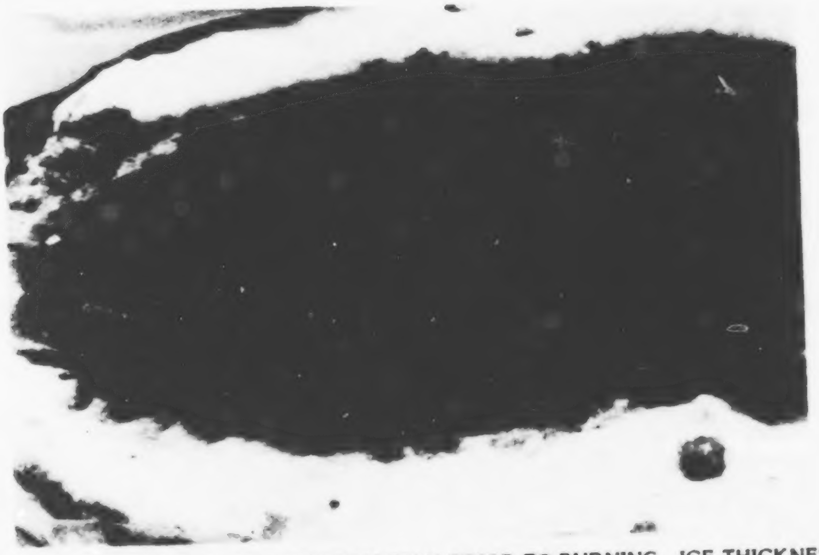

FIGURE 11 SITE A, JULY 7, 1982, IMMEDIATELY PRIOR TO BURNING. ICE THICKNESS 50 CM., OIL ON SURFACE IS 80% OF ORIGINAL VOLUME.

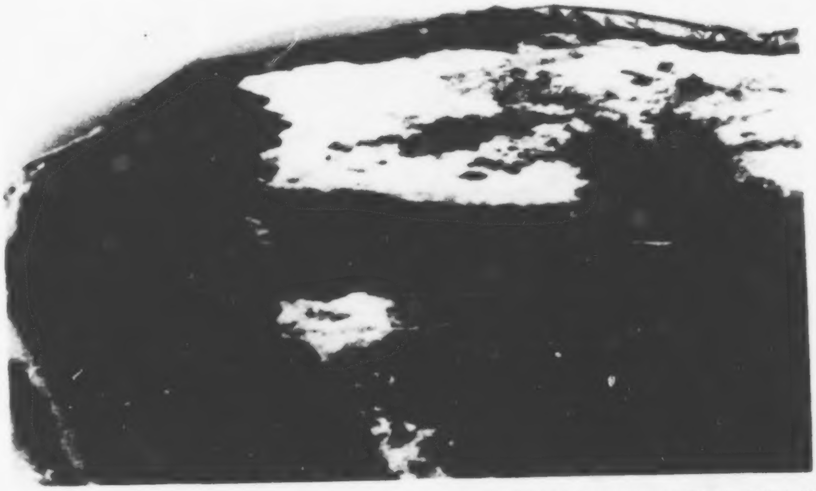

FIGURE 12 SITE B, JUNE 22, 1982, SHOWING OIL CONTINUALLY MIGRATING AND BEING HERDED INTO A SLICK (OIL ON SURFACE IS 5% OF ORIGINAL VOLUME)

The results plotted in Figure 14 as percent on the surface as a function of time confirm visual impressions recorded at the time. From the time of first oil appearance, the crude oil (Site B) was considerably more advanced in terms of oil on the surface than either of the two emulsion sites. This situation persisted until July 6. At that time, the emulsion surfaced very rapidly, as would be expected with the ice almost rotted completely through to the original oiled layer. The end result was that, of oil spilled under 165 cm of ice in March, about equivalent volumes of crude oil and emulsion were available for burning on the surface within 24 hours of ice breakup. Of more significance to the practical problems of cleaning up oil spilled under ice late in the winter (April to June) is the dramatic difference in actual migration rate between emulsion and crude oil. With as little as 3 days remaining until ice breakup on July 5, less than 15% of the original emulsion spill volume was floating on the surface although several holes were rotted clear through to the emulsion layer. By contrast, the crude oil site on the same date had over 50% of the original oil volume present as a slick on the surface. A logical physical explanation for the different behaviour of crude oil versus emulsion is that the greatly increased viscosity of the emulsion oil severely impeded natural vertical migration through the rotting ice.

FIGURE 13 CLOSE-UP OF EMULSION FLOATING ON SURFACE, SITE A, JULY 4, 1982 (LIGHT AREA ON LEFT INDICATES EMULSION STILL TRAPPED WITHIN THE ICE)

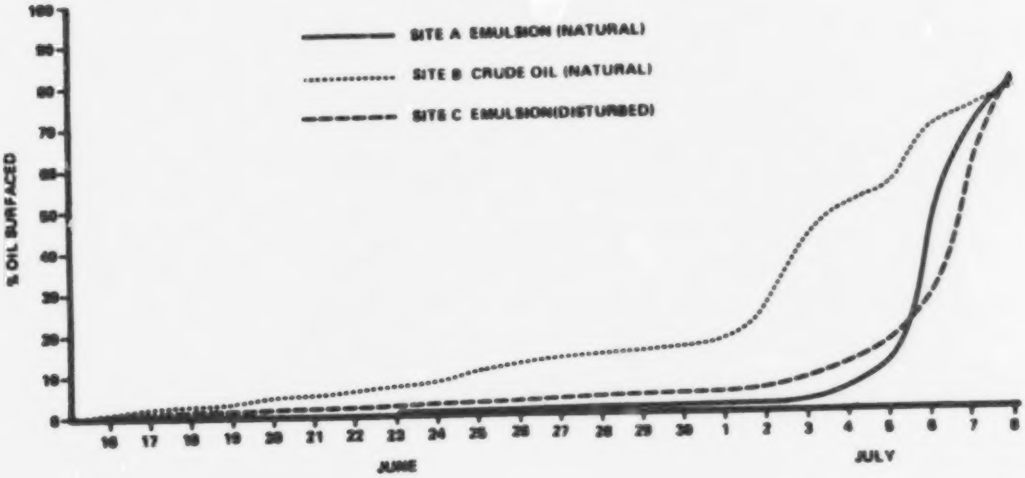

FIGURE 14 PERCENT OIL ON THE SURFACE AS A FUNCTION OF TIME

Significant emulsion surfacing was not possible even when a clear passage to the surface was available. The emulsion seems to have appeared on the ice surface by melting its way up through the sheet en masse. The emulsion was placed 165 cm below the ice surface in March. The ice sheet reached a total thickness of 180 cm, and breakup occurred when the ice was some 50 cm thick. For the emulsion to appear on the surface before breakup it must have melted up approximately 35 cm. This was confirmed by two facts:

a) on July 4, a 20 cm cavity below the emulsion was observed at Site A;

b) the polypropylene diver guide ropes frozen into the under-ice surface at the same time as the emulsion was discharged were still frozen in about 35 cm below the ice surface July 8;

One possible explanation for this behaviour is that, when the ice is still approximately 50 cm thick, the emulsion begins to be visible from the surface (e.g., Figure 13). As such, sunlight can penetrate and begin to warm the emulsion above ambient temperature, causing it to slowly melt the ice above it and float up.

### Cores

Cores were taken only in Site C, the second emulsion discharge, to avoid interference with the natural processes of oil exposure in the other two spills. (Although plotted for comparison in Figure 14, Site C oil exposure results are not considered representative of natural conditions.) Figure 15 shows a core taken in Site C on June 20. Total ice thickness at the time was 165 cm. The new ice growth which took place after discharge is visible on the left. The emulsion slush mixture is being spooned into a sample jar. No clear evidence of emulsion migration through the brine channels was observed in any of the cores (June 20, June 27, July 1). The colour and consistency of the emulsion collected from the core appeared visually the same as when pumped under the ice on March 20, 3 months earlier.

FIGURE 15 EMULSION BEING COLLECTED FROM CORE SAMPLE, SITE C, JUNE 20, 1982 (NEW ICE GROWTH AFTER DISCHARGE SHOWN BY CORE SECTION AT LEFT)

## OIL/EMULSION PHYSICAL AND CHEMICAL PROPERTIES

The crude oil used in this experiment was obtained from the Kopanoar 21-44 well in the southern Beaufort Sea. A stable water-in-oil emulsion was created by recirculating oil and water through a high-speed centrifugal pump. The properties of both the oil and emulsion prior to discharge are given in Table 1. In order to determine changes in the properties of the emulsion, a sample was taken from Site C 24 hours after the discharge. The properties of this sample are listed in Table 2. These data indicate that some minor dissolution of lighter components of oil has occurred. Laboratory solubility experiments indicated that the solubility of the oil in seawater was 12.3 ppm after 24 hours and peaked at 15.5 ppm after 120 hours. This converts to 0.3 and 0.4 weight percent of the original oil, respectively. The water content of the emulsion also dropped from 57% to 47%. This phenomenon has been observed with emulsions (Mackay and Zagorski, 1982), particularly those formed in intense mixing conditions.

TABLE 1 PRE-DISCHARGE OIL PROPERTIES

| Property | Crude Oil | Water-in-oil Emulsion |
|---|---|---|
| Density (g/cm$^3$) | | |
| 0°C | 0.8990 | a |
| 5°C | 0.8961 | 0.9607 |
| 20°C | 0.8863 | 0.9555 |
| Viscosity (cSt) | | |
| 10°C | 26.6 | 185 |
| 20°C | 15.5 | 93.8 |
| Pour Point (°C) | -1 | +4 |
| Flash Point (°C) | +38 | +74 |
| Fire Point (°C) | +66 | +96 |
| Water Content (wt %) | - | 57 |

[a]Sample froze

TABLE 2 24-HOUR POST-SPILL EMULSION PROPERTIES

| | |
|---|---|
| Density | = 0.9633 g/cm$^3$ @ 20°C |
| Viscosity | = 100.5 cSt @ 20°C |
| Pour Point | = 4°C |
| Flash Point | = 77°C |
| Fire Point | = 99°C |
| Water Content | = 47 wt % |

Samples of the emulsion from Site C were obtained periodically throughout the spring. The purpose of these samples was to document any changes in the emulsion properties while it was frozen in the ice. The core samples were spooned into jars, frozen for storage, and shipped at the end of the field work via air freight. The oil was at least partly emulsified when it arrived in British Columbia for analysis by GC and for water content. By the time density, viscosity and flash point measurements were made, the samples had separated into distinct oil and water phases.

It is apparent that the sample handling and storage caused the emulsions to "break". It is worth emphasizing that the physical appearance and behaviour of the emulsions at the test site during spring confirmed that the emulsions had not "broken" significantly. The consistency of the emulsion was that of peanut butter; mats of the emulsion would be partially submerged after a rainfall.

Figure 16 illustrates the change in emulsion water content with time. After the initial drop immediately after discharge, the water content remained relatively constant throughout the emulsion's period of encapsulation. The increase in water content upon exposure to the atmosphere may result from sampling errors, or it may reflect a relative increase in water due to evaporation of hydrocarbons combined with rain. The water content of the surface oil on the crude oil test plot in July was measured at between 4 to 5%.

Table 3 shows the weathering of the crude oil. The increase in density, viscosity, and flash point, and the evaporative losses are consistent with other Arctic field trials (NORCOR, 1975; Dome, 1981). The evaporative loss for the emulsion samples was measured as approximately 15% for all core and surface samples. The difference between oil and emulsion evaporative losses is within the error bounds of the analysis technique and is not considered significant. Loss of light ends from oil trapped in ice, particularly after the sheet has become porous, has been observed at previous Arctic field trials (NORCOR, 1975; Dome, 1981).

In summary, the crude oil behaved as would be expected. The emulsion did not "break" significantly during its encapsulation in the ice and appeared on the surface of melt pools in essentially the same form as when it was discharged. The evaporative losses for both crude oil and emulsion were comparable.

## COUNTERMEASURES

The main objective of this experiment was to determine whether or not an emulsion spilled under first year sea ice could be cleaned up using in situ burning the following spring. On July 7 and 8, both in situ burning and manual recovery of oil and emulsion took place. Breakup occurred at the site during July 9 and 10. Following removal of all surface oil, the skirts, ropes, cameras and litter were removed from the ice surface.

### In Situ Burning

Table 4 presents the results of the burning. The crude oil (Site B) was burned off on July 7. Ignition was achieved easily using a gasoline-soaked sorbent pad and a match. The burn was intense and resulted in the disposal of some 86.4 kg of oil. Figure 17 illustrates the burns at Site B. The next day, an additional 12.8 kg of reherded oil and residue were burned. Thus, in total 99.2 kg, or some 57%, of the oil originally discharged was disposed of by in situ burning. This translates to an individual pool burning efficiency of 73%. These results are consistent with those obtained in earlier oil-in-ice field experiments (NORCOR, 1975; Dome, 1981).

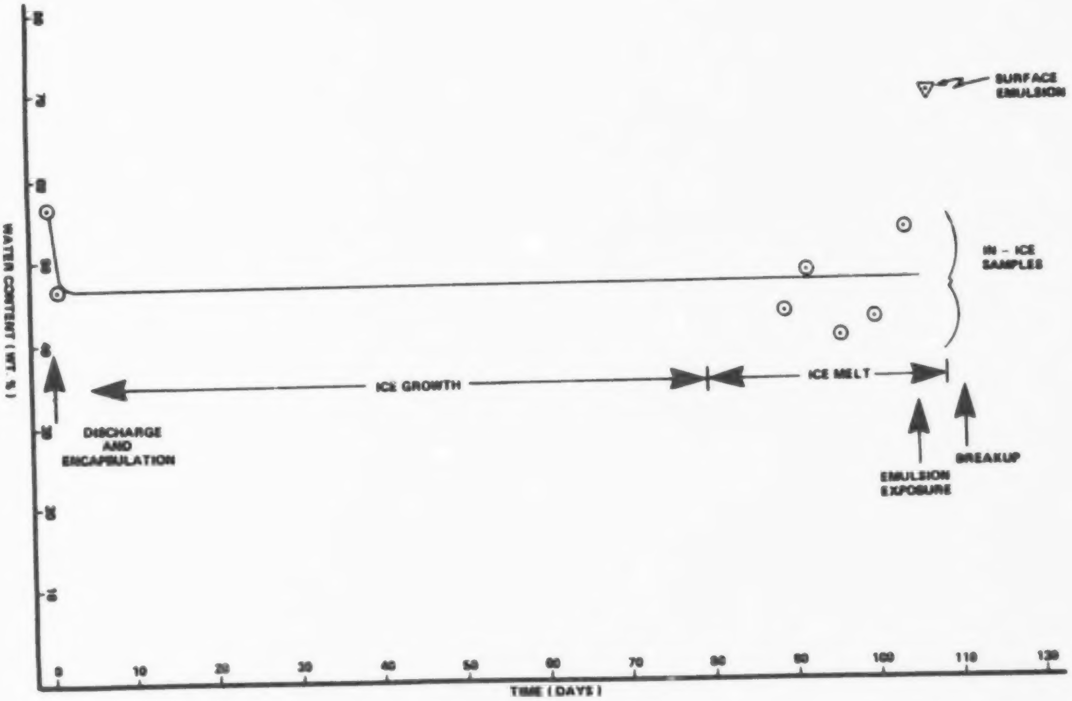

FIGURE 16 EMULSION WATER CONTENT VS TIME

TABLE 3 CRUDE OIL WEATHERING

| Sample | Density (g/cm$^3$ @ 20°C) | Viscosity (cSt @ 20°C) | Flash Point (°C) | Evaporation (wt %) |
|---|---|---|---|---|
| Prespill | 0.8863 | 15.5 | 48 | 0 |
| July 2 (surface) | 0.8907 | 20.0 | - | 13 |
| July 7 (surface) | 0.8983 | 33.4 | 156 | 13 |

TABLE 4 IN SITU BURNING RESULTS

| | Site A[a] (emulsion) | | Site B (crude oil) | | Site C[a] (emulsion) | |
|---|---|---|---|---|---|---|
| Burn No. | Oil Burned (kg) | Pool Efficiency | Oil Burned (kg) | Pool Efficiency | Oil Burned (kg) | Pool Efficiency |
| 1 | 16 | 26% | 86.4 | 64% | 1.4[b] | 2% |
| 2 | 20 | 42% | 12.8 | 26% | 7.2 | 12% |
| 3 | 3.5 | 13% | - | - | - | - |
| Overall | 39.5 | 63% | 99.2 | 73% | 8.6 | 14% |

[a] Results presented on a water-free basis.

[b] This was preceeded by several unsuccessful ignition attempts using gasoline which resulted in an inability to achieve sustained combustion after successive ignitions.

FIGURE 17 BURNING AT SITE B

The emulsion at Site C was used to experiment with ignition techniques as this site had been extensively cored and the oil exposure rate was not felt to be representative. Solid propellant ignitors were not used as an ignition source because their delivery to the test site was delayed until after breakup by poor flying conditions. A previous study (Twardus, 1980) has reported that it is possible to ignite water-in-oil emulsions using solid propellant ignitors. In some cases, the addition of fresh crude oil was required as a promoter.

Three methods of ignition were tried at Site C, namely: gasoline poured onto the emulsion, gasoline soaked sorbent pads placed on the emulsion, and diesel soaked sorbent pads placed on the emulsion. Although the first two techniques did result in intense flames, they quickly extinguished once the gasoline was consumed, and resulted in little or no emulsion burning (Figure 18). The use of diesel soaked sorbent pads proved quite successful as the diesel would burn hotter and for a longer time. This resulted in sufficient heat radiated to the emulsion to cause the surface to "break". The resulting crude oil would then ignite and burn (Figure 19). As several ignition attempts had already been made with gasoline, the flames did not propagate significantly, probably due to a reduction in light hydrocarbons in the surface layers of the emulsion. Attempts to conduct further burns were abandoned and Site C was cleaned using sorbents.

FIGURE 18 UNSUCCESSFUL IGNITION OF EMULSION, SITE C, USING GASOLINE-SOAKED SORBENT PADS

Burning operations were conducted at Site A the following day (July 8) using diesel-soaked sorbent pads. The sorbents proved to be an efficient ignition source and some 36 kg of oil (equivalent to 90 kg of emulsion) were combusted in two burns (Figure 20). A final burn was conducted after herding the residue against an ice edge. This resulted in the combustion of an additional 5.3 kg of oil. In total, some 30% of the original oil, in the form of an emulsion, was disposed of by in situ combustion. The first two burns resulted in individual pool burning efficiencies of 26% and 42%, respectively. The overall pool burning efficiency was 63%.

The pool burning efficiencies reported here for the emulsions at Site A are 20 to 30% less than have been reported by others (Energetex 1980; Mackay and Zagorski, 1982). The earlier lab-scale experiments were performed with

FIGURE 19 SUCCESSFUL IGNITION OF EMULSION, SITE A, USING DIESEL-SOAKED SORBENT PADS. EMULSION IS BREAKING AND FEEDING FLAMES.

FIGURE 20 INTENSE BURN OF EMULSION AT SITE A

slicks of $3 \times 10^{-3} \times 10^{-3}$ $m^2$ (Mackay and Hossain, 1980) and 1 $m^2$ (Edwards, 1980). Since the burns conducted with emulsions during this experiment rarely covered the entire surface area of the slick, reduced pool burning efficiencies would be expected. It seems that there may be a limiting size for an emulsion fire as compared to the crude oil fire. Consideration should be given to investigating this phenomenon further. It was concluded that although more difficult to ignite and requiring a greater number of ignitions emulsions can be burned off with efficiencies comparable to the crude oil.

### Manual Cleanup

Following the completion of *in situ* burning operations at each site, sorbents were used to recover all the remaining surface oil. At Site B (crude oil), 35.9 kg of oil and burn residue were collected. At Site A (emulsion), 23.4 kg of oil, equivalent to 58.3 kg of emulsion, were collected. At Site C (emulsion), 33.9 kg of oil, equivalent to 133 kg of emulsion, were collected. Again, the large volume of oil collected manually at Site C was a direct result of using this site to experiment with emulsion ignition.

### Mass Balance

Table 5 shows the calculated mass balance based on dissolution losses, evaporation, burning and manual cleanup compared to the known mass of oil discharged. It should be noted that the balance for the emulsions was prepared on an "oil only" basis. This was due to the fact that dissolution, evaporation and burning rates could only be measured for the oil component of the emulsion.

TABLE 5 MASS BALANCE ON OIL

| | Site A (Emulsion) | Site B (Crude Oil) | Site C (Emulsion) |
|---|---|---|---|
| Oil Discharged (kg) | 79 | 173 | 79 |
| Oil dissolved during encapsulation (kg) | 0.3<br>(0.4%)[a] | 0.7<br>(0.4%) | 0.3<br>(0.4%) |
| Oil evaporated during encapsulation and surface exposure (kg) | 11.5<br>(15%) | 21.8<br>(13%) | 11.5<br>(15%) |
| Oil burned *in situ* (kg) | 39.5<br>(50%) | 99.2<br>(57%) | 8.6[b]<br>(11%) |
| Oil recovered manually (kg) | 23.4<br>(30%) | 35.9<br>(21%) | 53.9[b]<br>(68%) |
| Oil left in ice at breakup (kg) | 4.3<br>(5%) | 15.4<br>(9%) | 4.7<br>(6%) |

[a] Percentage of oil discharged.

[b] This site was used to experiment with ignition of the emulsion then cleaned manually.

Immediately after discharge and until the oil or emulsion was encapsulated, it was estimated that some 0.4% of the mass of oil dissolved in the water column. This estimate was based on a laboratory solubility test. The amount of oil lost to evaporation during and following its appearance on the ice surface was calculated from gas chromatographic (GC) analysis of core and surface samples. These GCs were compared to those of samples weathered in the lab. The results indicate that both the emulsion and crude oil weathered to a similar degree in and on the ice. It has been speculated that the formation of an emulsion by an oil would reduce evaporation (Mackay and Zagorski, 1982); however, in this experiment at least, this does not seem to be the case over a long time period.

The mass of oil left in the ice at breakup was calculated by subtracting the mass of oil dissolved, evaporated, burned and recovered, from that originally discharged. At first glance, it appears that more crude oil than emulsion was left in the ice. It must be remembered, however, that the emulsion mass balance is expressed on an "oil only" basis. The masses of oil left in Sites A and C translate to 11 and 12 kg of emulsion, respectively. If converted to volumes (a more reasonable basis for comparing amounts of oil left in ice), the emulsion sites contained approximately 11 and 12 L of emulsion and the crude oil site contained approximately 13 L of oil. The differences are negligible.

### Implications for Offshore Countermeasures

There are three conclusions drawn from this study that have implications for offshore countermeasures in ice-covered waters. These relate to: firstly, the timing of emulsion appearance in spring; secondly, the total mass of emulsion appearing in spring; and finally, the ability to ignite and burn emulsions *in situ*.

The timing of emulsion appearance in spring is related to the time of the year it is spilled under the ice and the type of ice it is deposited beneath. For emulsions spilled under first year sea ice less than 165 cm thick, the emulsion will appear on the ice surface prior to breakup (assumed to occur when the ice melts to 50 cm). By comparing the ice growth curve (Figure 3) and the ice ablation curve (Figure 6), it can be seen that emulsion placed under the ice in November would have been completely exposed by no later than June 23. Similarly, an emulsion spilled January 15 would be completely exposed by no later than July 3. The emulsion spilled March 20 was 90% exposed by July 8. Presumably, emulsions spilled under the ice in April would not have appeared until breakup was well advanced. Thus, in general, it can be concluded that emulsions spilled under ice less than 120 cm thick will appear the following spring at least 1 week prior to breakup. Emulsions spilled under ice between 120 and 165 cm thick will appear at least 2 days prior to breakup. Emulsions spilled under ice much thicker than 165 cm may not appear until breakup is advanced.

Since brine channel migration played no part in the exposure of the emulsions in this experiment, it can be presumed that emulsions spilled under multi-year ice would take much longer to surface than would straight oil.

Perhaps the greatest impact of this experiment on full-scale operations is the number of ignitions required. It was observed that to achieve a similar volumetric burn efficiency, twice as many ignitions of emulsion were required compared to crude oil. Since it is probable that an under-ice blowout would not form an emulsion as intensely mixed as was created for this experiment, the situation of having to double the number of ignitions can be regarded as a worst case.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

1. The water-in-oil emulsion appeared on the ice surface prior to breakup in time for cleanup. Only 5 to 6% of the oil was left in the ice at breakup.
2. The comparison between crude oil and emulsion showed that there was no significant difference between the volumes of oil and emulsion that had appeared by breakup.
3. The emulsion did not appear as soon or as quickly as the crude oil did.
4. It was possible to burn the emulsion in situ with an overall efficiency of 50% by weight, similar to that of the crude oil (57%).
5. Twice as many ignitions were required for the emulsion as compared to the crude oil.
6. The emulsion did not "break" during its encapsulation in the ice sheet or during its exposure on the ice surface.
7. The crude oil migrated to the ice surface in spring through brine channels. The emulsion appeared by a combination of ice ablation and by melting its way en masse up through the ice.
8. There was no significant difference in the evaporative/dissolution losses between the emulsion and the crude oil.
9. Both the emulsion and crude oil were encapsulated by the growing ice sheet within 48 hours of their discharge.

### Recommendations

1. The oils found and used in Canada's offshore areas should be classified according to the stability of the water-in-oil emulsions they form.
2. Investigations into the in situ burning of water-in-oil emulsions on larger scales should be undertaken.
3. Measurement of the physical properties of water-in-oil emulsions should be made as soon as possible, preferably immediately after sampling.

## ACKNOWLEDGEMENTS

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# LONG-TERM FATE OF CRUDE OIL IN THE ARCTIC NEARSHORE ENVIRONMENT - THE BIOS EXPERIMENTS

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## ABSTRACT

A summary of the results from the BIOS 1982 (1 year post-spill) field sampling and chemical analysis program is presented. Petroleum hydrocarbons persist in the offshore sediments of the test bays, with levels increasing at the site of the untreated oil spill (Bay 11) where oil had impacted the beach previously. Levels in the water column are low, but detectable low-molecular-weight alkanes and aromatic hydrocarbons are observed. These compounds, in turn, are being acquired by the filter-feeding benthic animals. Residual levels of oil in the animals are low, 1-60 ppm, 1 year after the spills, but a continuing impact is noted in Bay 11. Possible sources of oil to the water column and benthos of the various bays are discussed.

## INTRODUCTION

As part of the continuing studies on the comparative transport and fate of untreated crude oil and chemically dispersed oil introduced into the Arctic nearshore environment during the Baffin Island Oil Spill (BIOS) program (Blackall and Sergy, 1983; Boehm et al., 1982b), we report here a summary of the findings based on the study undertaken during the 1982 field season.

The BIOS project's nearshore study focuses on the impacts of two controlled spills of 15 $m^3$ of Lago medio crude oil onto the surface (untreated spill) of Bay 11 of the Ragged Channel region of Cape Hatt, N.W.T. (Figure 1) and into the water column (chemically dispersed spill) of Bay 9. Previous study of the movement and short-term (2 to 3 weeks post-spill) fate of the spilled oils showed that water column impacts in the untreated spill scenario in Bay 11 were minimal, the major impact occurring on the beach itself (Green et al., 1982; Boehm et al., 1982a), with only very minor amounts of oil being sedimented or otherwise transported to the nearshore benthos. By contrast, the water column impact resulting from the chemically dispersed spill scenario in Bay 9 resulted in very high levels of waterborne oil in this bay, with exposure levels of 20-900 ppm-h in Bay 9 and 10-40 ppm-h in Bay 10 (Green et al., 1982). Relatively low levels (up to 10 ppm) of oil were reported in the benthic sediments of these bays, accounting for much less than 1% of the total oil introduced (Boehm et al., 1982a). Low levels of oil (< 50 ppm) were observed in the water column of Bay 7, the "control" bay, and at other locations in Ragged Channel (Green et al., 1982).

During the acute and short-term post-acute (1 day - 2 weeks) impact phases, benthic animals acquired large amounts of both the waterborne oil and subsequently of the sedimented oil, with the filter-feeding bivalves *Mya truncata* and *Serripes groenlandicus* acquiring 100-700 ppm of waterborne oil initially. The deposit-feeder *Macoma calcarea* continued to acquire oil during the first 2 weeks after the spill (up to 860 ppm in Bay 9), as did the sea urchin *Strongylocentrotus droebachiensis* (up to 240 ppm in Bay 9) (Boehm et al., 1982b), presumably due to their acquisition of sedimented oil residues. Details of the chemical nature of the early uptake and depuration activities of these animals has been previously presented (Boehm et al., 1982b).

This report is a continuation of previous presentations (Boehm et al., 1982a,b) and discusses the major findings on the levels and chemical composition of oil residues found in water, sediments, and benthic animals obtained during the summer of 1982, one year after the spills. The goals of this phase of the chemical studies of the BIOS program are shown in Table 1.

## METHODS

Sampling and analytical strategies and methods have been previously described (Boehm et al., 1982a,b; Green et al., 1982; Humphrey, 1983). Each bay was sampled once during August, 1982, although additional samples were taken in some locations in May and September. Analytical methods included UV/fluorescence to quantify levels of residual oil, high resolution gas chromatography ($GC^2$) to identify and quantify the petroleum hydrocarbons present in the samples, and gas chromatographic mass spectrometry ($GC^2$/MS) to identify and measure the concentrations of aromatic hydrocarbons in the samples.

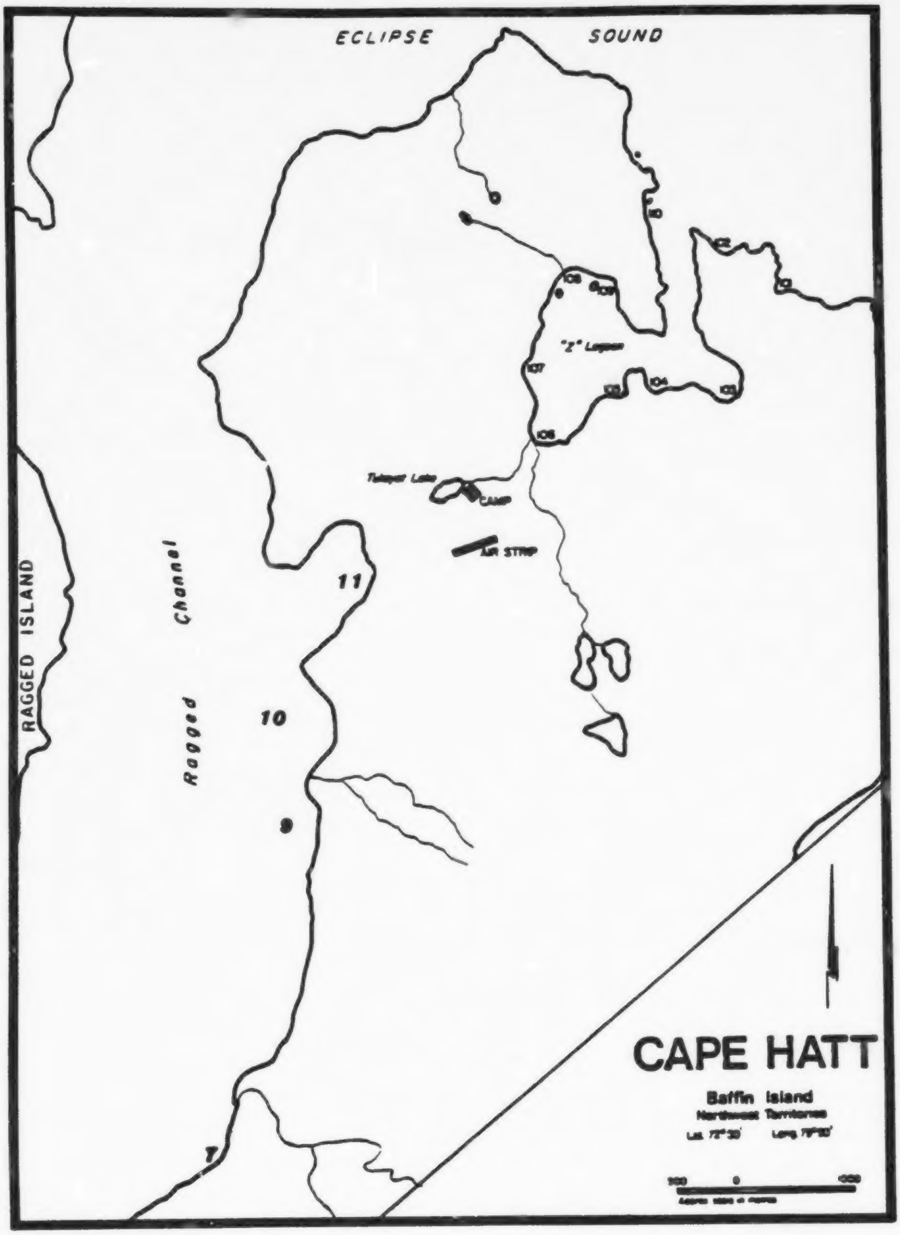
ECLIPSE
SOUND
110
102
101
108
109
"Z" Lagoon
107
103
104
105
106
CAMP
AIR STRIP
11
10
9
7
RAGGED ISLAND
Ragged Channel
CAPE HATT
Baffin Island
Northwest Territories
Lat. 72°30'
Long. 79°50'
500
0
1000
Approx. scale in metres

FIGURE 1 DETAIL OF TEST BAY LOCATIONS AT CAPE HATT, BAFFIN ISLAND

TABLE 1 BIOS PROJECT: HYDROCARBON BIOGEOCHEMISTRY GOALS (YEAR 3)

1. To compare the composition and fates of oil as it impacted the four bays.
2. To examine the composition and concentration of high-molecular-weight petroleum components in a limited set of water column samples taken from the four bays.
3. To examine the chemical nature and weathering of residual surface oil and beached oil.
4. To explore the compositional fractionation of waterborne oil into dissolved and particulate classes.
5. To examine the composition and concentration of oil in bottom sediments and the related presence of oil in the suspended materials in the water column through sediment-trap samplings.
6. To analyze bottom sediments from all bays for oil content, composition, and weathering changes and to examine the relation of bulk sediment hydrocarbon chemistry to that of the deposited surface flocculent layer in Bay 11. To examine possible trends in biodegradation, to examine possible offshore transport of the oil.
7. To examine the depuration of petroleum residues by several species of benthic marine organisms, and to examine how these processes varied by species, by bay.

## RESULTS

### Water Column

Petroleum concentrations in the water column of the study area were quite low. The highest concentrations of oil in the water were found in Bay 11 where levels in the intertidal region were 3 μg/L (3 ppb). These "higher" level samples were taken under areas where a visible oil sheen was observed emanating from the beached oil mass. Fractionation of the waterborne oil into dissolved and particulate residues indicated a prevalence of the soluble two-ringed aromatics in the dissolved fraction, with the particulate petroleum aromatics consisting primarily of the three-ringed phenanthrene and dibenzothiophene compounds. Samples of the surface sheen indicated that a disproportionation was occurring, with the low-molecular-weight aromatics being preferentially lost from surface oil and the low-molecular-weight saturates remaining in the oil layer. Thus, the saturated hydrocarbon weathering ration (SHWR) (see Boehm et al., 1982a) was typical of an unweathered or lightly weathered oil (i.e., little evaporative loss), while the aromatic weathering ratio (AWR) illustrated a high degree of weathering (i.e., loss due to solubilization).

Only very low, <100 ng/L (100 parts per trillion), levels of oil were found sporadically in other samples from this and the other bays. Interestingly, the Bay 7 samples contained 30-100 ng/L of oil, with an enhancement of the low-boiling n-$C_{10}$ through n-$C_{15}$ alkanes. Aromatics were not analyzed in these samples.

### Oil in the Sediments

Levels of residual oil in the sediments from Bays 9 and 10 were low, 1-3 ppm in Bay 9 and 1-2 ppm in Bay 10. This represents a significant decrease in Bay 9 levels where the last values observed 2 weeks after the spill were as high as 20 ppm (geometric mean = 9.0 ppm). Levels in Bay 10 in 1982, however, were similar and only slightly lower than those observed 2 weeks after the spill. Low levels (1-2 ppm) were also observed in Bay 7 sediments.

The levels in Bay 11, however, had increased 1 year after the spill by over an order of magnitude, with values as high as 66 ppm being observed (geometric mean as high as 10 ppm). A very patchy distribution of oil marked the Bay 11 sediments. High levels of oil were also observed in the surface floc layer, thus indicating recent inputs of oil.

That the oil in the Bay 11 sediments originated from the beach is indicated by the close similarity in chemical composition (by GC$^2$) of oil on the beach, in the floc, and in the higher surface sediment concentrations. This oil was observed to be somewhat biodegraded, as noted in the increased (>1.0) phytane/n-$C_{18}$ ratio and in the ratio of other isoprenoid alkanes/normal alkanes. Note that the oil on the Bay 11 beach was significantly biodegraded (Figure 2) (phytane/n-$C_{18}$ = 1.0-2.3, as compared with 0.6 in the spilled oil).

The moderately biodegraded oil on the Bay 11 beach serves as a good marker of this Bay 11 beached oil, as significant biodegradation (greater than a 20% change in the phytane/n-$C_{18}$ or alkane/isoprenoid (Boehm et al., 1982a) ratio) was not observed in any sediments from Bays 7, 9, and 10 (see Boehm, 1983). Thus, it appears that biodegradative removal pathways for the oil are only significant during the 1 year post-spill period on the beached oil.

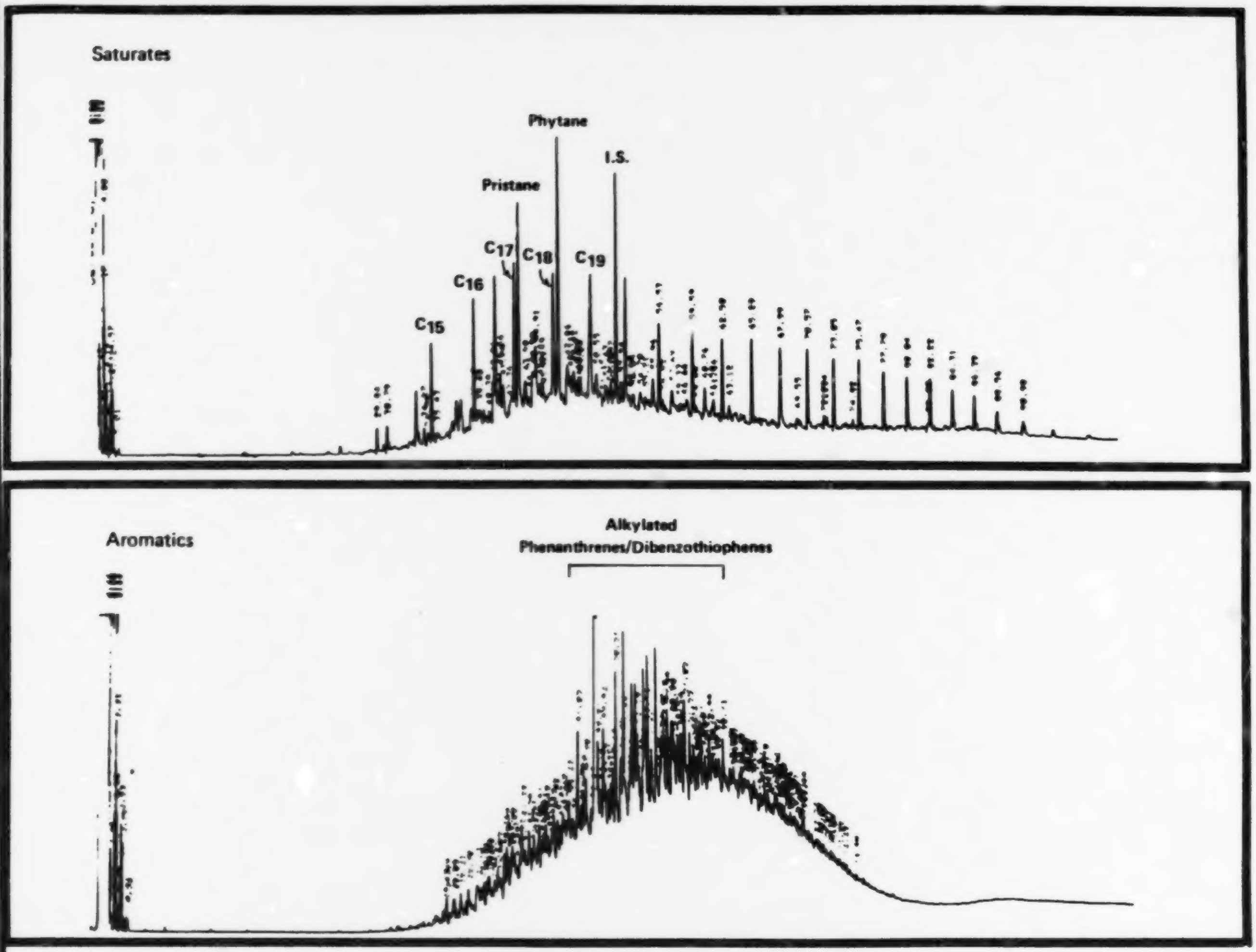

FIGURE 2 GAS CHROMATOGRAMS ILLUSTRATING COMPOSITION OF OIL ON BAY 11 BEACH

The comparative chemistries of oil stranded on the beaches of Bays 11 and 9 were quite revealing. As previously discussed, the residues of oil on Bay 11 (2,000-7,000 ppm) were significantly weathered and biodegraded. Much lower quantities of residual oil were found on the Bay 9 beach (dispersed oil scenario) in 1982. Five of the six samples analyzed contained 1-2 ppm, while one sample contained 21 ppm. The chemical nature of these oil residues (Figure 3) is quite different from that of Bay 11 beached oil, in that a) the oil on Bay 9 was not biodegraded (phytane/n-$C_{18}$ = 0.5-0.7), and b) the chemical composition resembled a mix of undegraded paraffinic oil and an aromatic fraction closely resembling a water-soluble fraction of oil, with significant quantities of naphthalenes and alkylated benzenes present (Figure 3c). Possible origins of this "fresh" oil are discussed below. The presence of these low-boiling aromatics here and in the sediments and benthic animals is possibly linked.

In nearshore sediments of higher total oil concentrations, aromatic hydrocarbon residues resembled weathered oil as previously observed late in 1981, with the alkylated phenanthrene and dibenzothiophene compounds dominating (see Figure 4b). However, at lower oil concentrations, the naphthalene compounds became relatively important. Generally, aromatic hydrocarbon levels in the sediments were not lower than levels observed in 1981 and, indeed were substantially higher in most cases. For example, levels of individual petroleum aromatics in the Bay 9 (7 m) sediment were 5-10 ppb in 1981, but at the time of the 1982 sampling had apparently increased two- to fivefold in spite of an overall decrease in the "total oil" values. In Bay 11, individual aromatic hydrocarbon levels were much higher than in 1981, with 1982 values typically 10-50 ppb (total ~ 150 ppb). Where higher oil concentrations were observed at the south end of the benthic sampling lines, aromatic hydrocarbon levels as high as 300 ppb were observed.

A single $GC^2$/MS analysis of a Bay 7 (control) sediment revealed individual aromatic compound levels of 5-20 ppb (total ~ 70 ppb), with a significant input of naphthalene compounds.

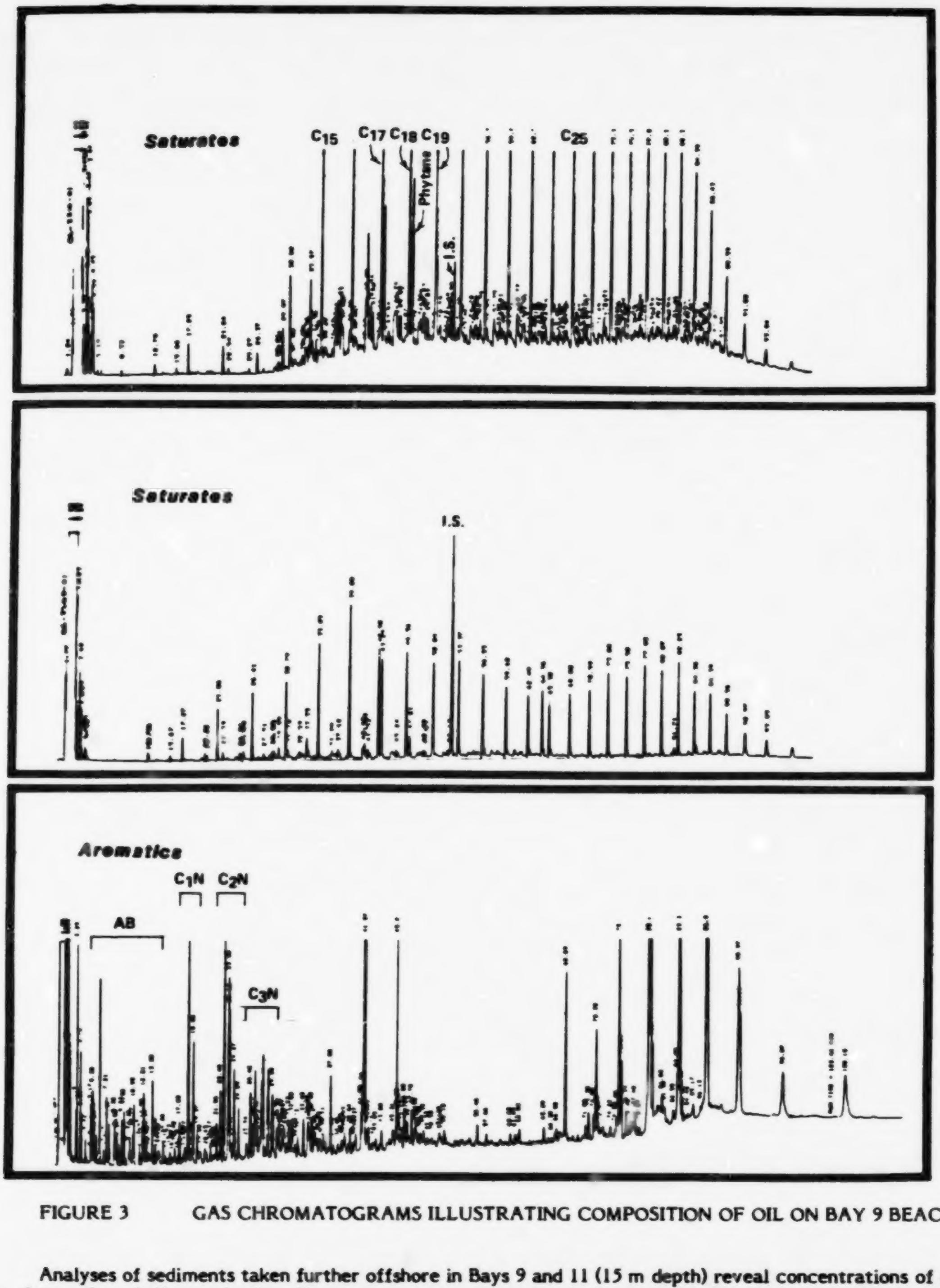

FIGURE 3 GAS CHROMATOGRAMS ILLUSTRATING COMPOSITION OF OIL ON BAY 9 BEACH

Analyses of sediments taken further offshore in Bays 9 and 11 (15 m depth) reveal concentrations of oil similar to those observed at shallower depths. However, no gross transport of oil was indicated. Such increases would have been revealed by increasing concentration gradients offshore. Additionally, analysis of core samples from Bays 9 and 11 revealed that low levels of petroleum, as indicated by $GC^2/MS$ analyses of aromatic residues, may have been mixed or otherwise penetrated down to 10-15 cm within the sediment column.

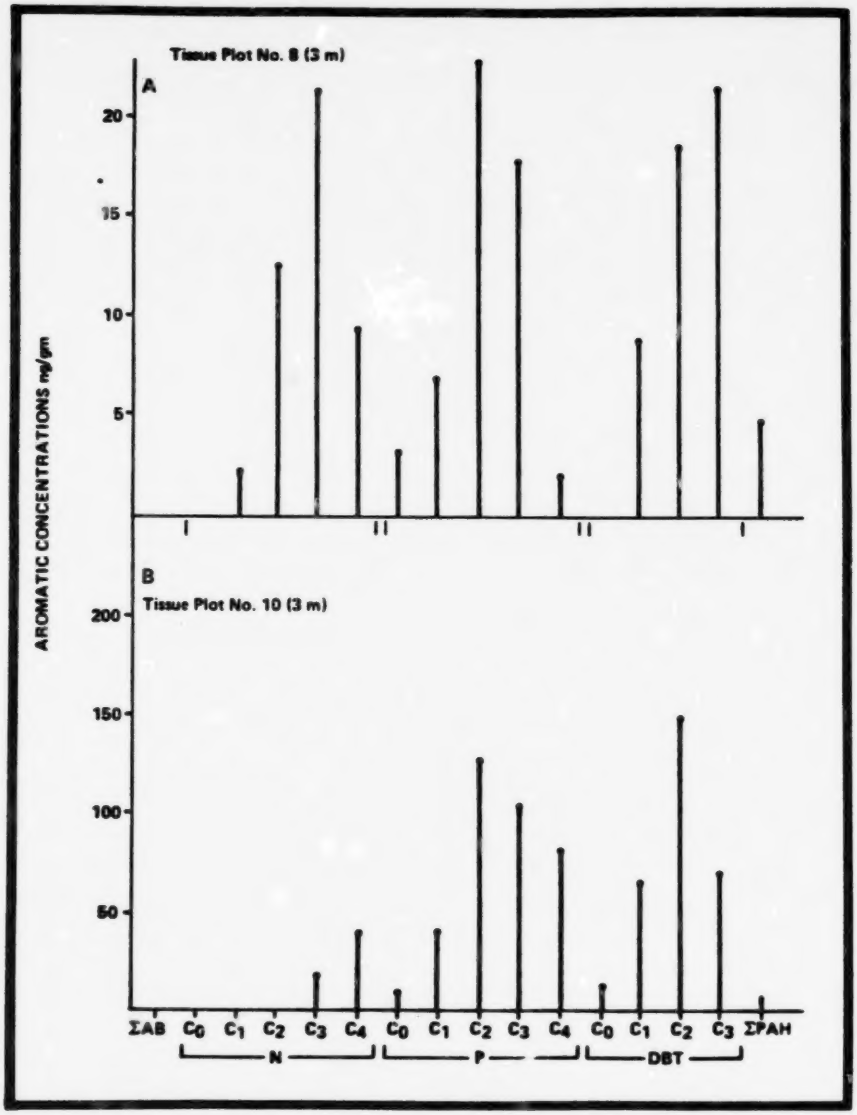

FIGURE 4 GC/MS RESULTS FROM BAY 11 SEDIMENTS

## Oil in Benthic Organisms

Overall trends in the oil concentrations for the five indicator species in the four bays are shown in Figures 5, 6, 7 and 8. While the oil levels in all species in all of the bays decreased markedly between September, 1981 and August/September, 1982, some details of the depuration sequence are noteworthy.

Uptake/depuration curves from Bay 9 (Figure 5) indicate that while oil levels in all species decreased by August, 1982, an increase was observed in the urchins at the time of a May, 1982 sampling. The single analysis yielded a concentration of 760 ppm, up from 230 ppm in August, 1982. Residual levels of oil in the deposit-feeders *Macoma* and in the urchins were higher than in the filter-feeders. Gross oil levels of oil in *Mya* in Bay 9 and in the other bays were very low (~ 1 ppm).

In Bay 10, a similar apparent increase in oil levels in urchins was observed with levels in May, 1982, up to ~ 200 ppm and thereafter decreasing. Residual oil levels in all species were low in August, 1982 (Figure 6).

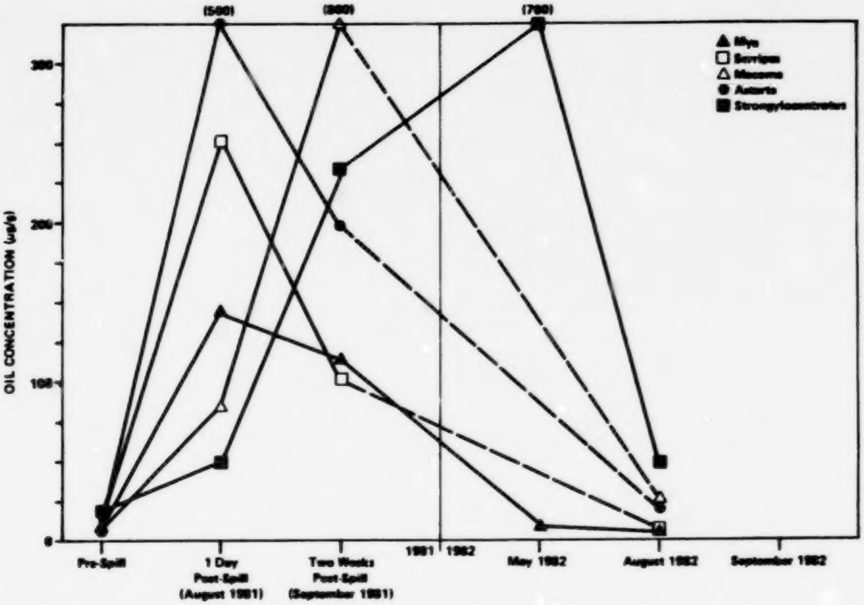

FIGURE 5 OIL CONCENTRATIONS IN ANIMALS FROM BAY 9

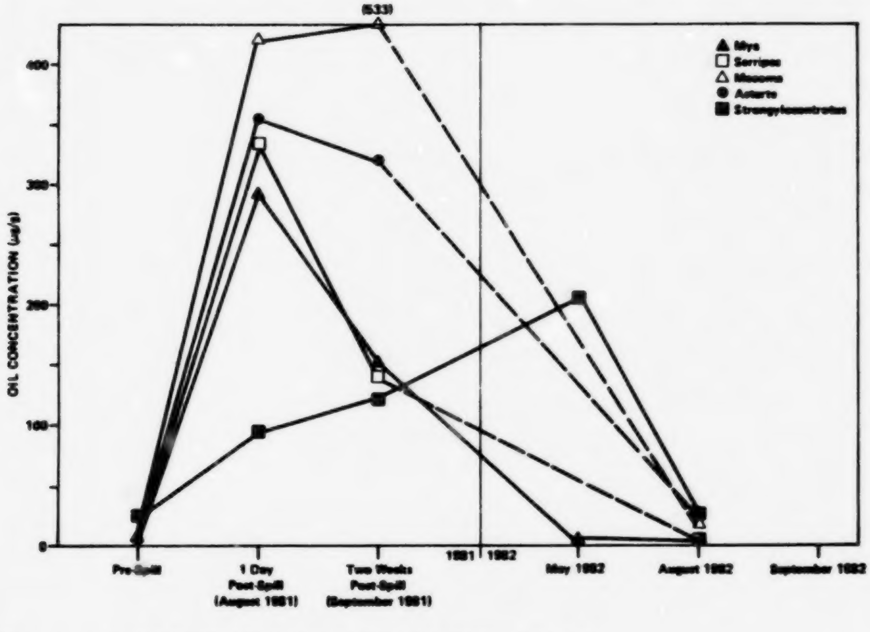

FIGURE 6 CONCENTRATIONS IN ANIMALS FROM BAY 10

After an initial (1981) uptake of waterborne oil, the animals of Bay 7 apparently steadily depurated the oil until levels for all species, though detectable, were quite low (1-10 ppm) (Figure 7).

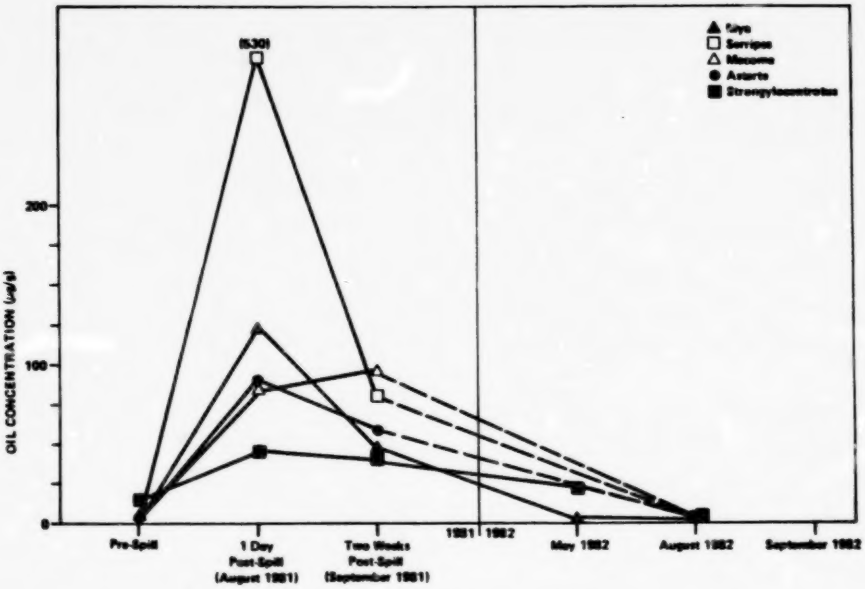

FIGURE 7 OIL CONCENTRATIONS IN ANIMALS FROM BAY 7

The initial uptake of oil by animals in Bay 11 was delayed somewhat until oil residues were transported off the beach (Figure 8). Thereafter, in spite of continuing and increasing transport to the benthos, tissue levels steadily decreased through August, 1982. At this time, however, residual levels in the deposit-feeders were higher (urchins, 46 ppm; *Macoma*, 60 ppm) than comparable levels in the other bays. Residual low levels in the filter-feeders suggested that additional water-mediated uptake of oil was not significant. Results from a final sampling in September (Figure 8) suggest that levels in the animals may have been increasing (urchins, 60 ppm; *Mya*, 5 ppm).

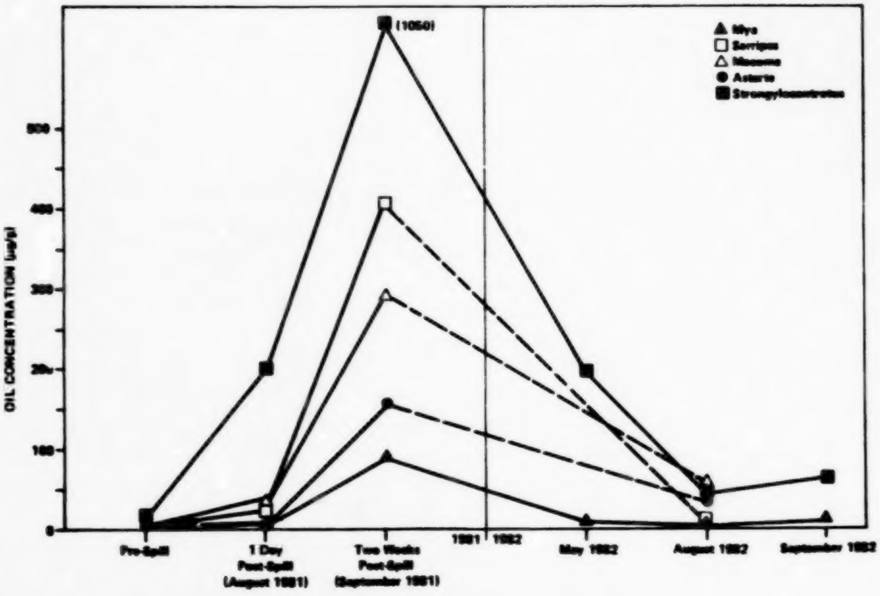

FIGURE 8 OIL CONCENTRATIONS IN ANIMALS FROM BAY 11

Compositional profiles ($GC^2$, $GC^2$/MS) of oil in the tissues indicated that although oil levels in the filter-feeders were low, a low-molecular-weight "overprint" of low-boiling alkanes and two-ringed aromatics appeared in the $GC^2$ traces of the filter-feeders (e.g., Figure 9). Between the 1-day post-spill sampling and the 2-week (September, 1981) sampling, naphthalenes were seen to be lost from the tissues due to depuration of initially acquired oil. Here in 1982, we see considerable levels of these compounds reappearing in the animals often at the 100-200 ppb level (e.g., Figure 10).

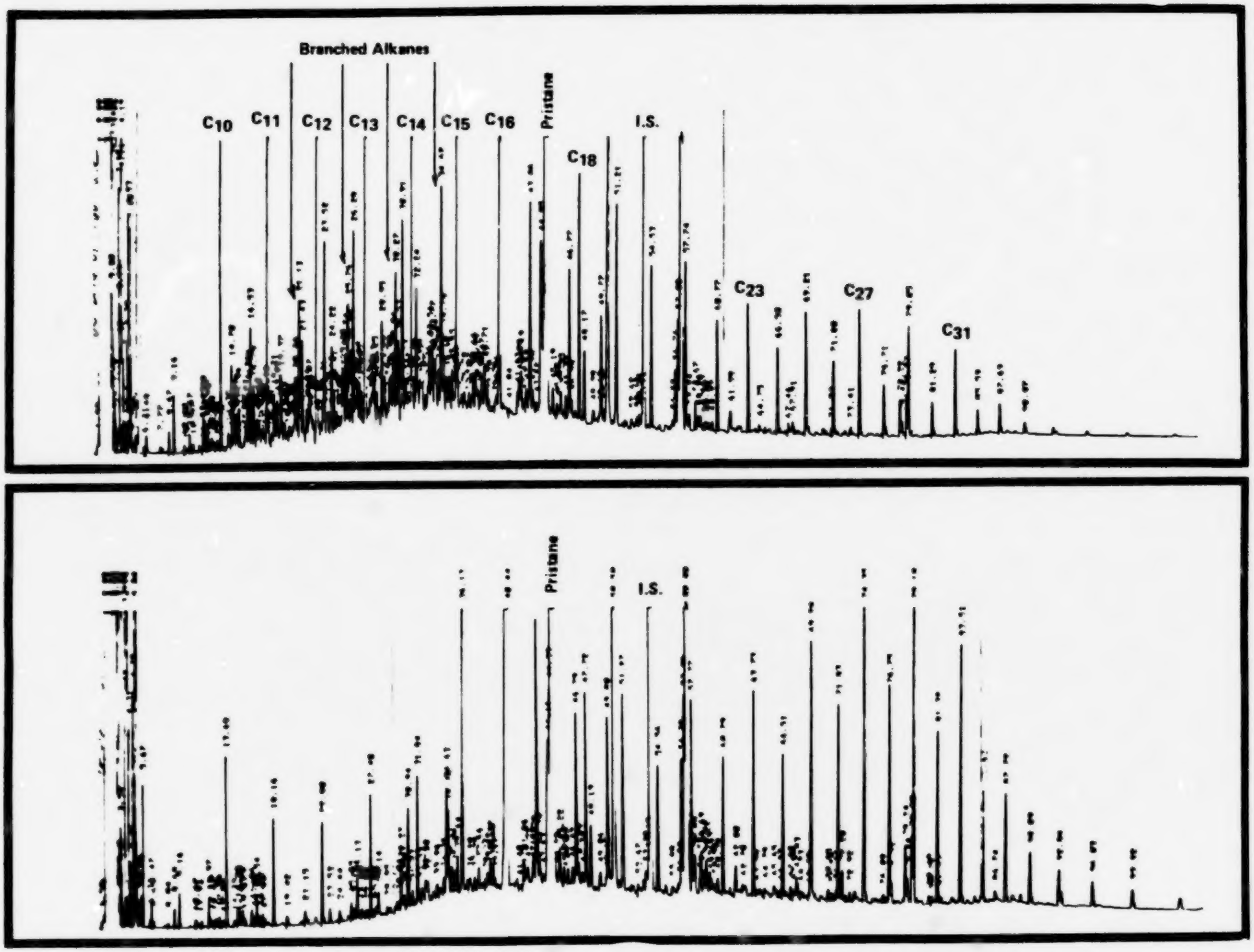

FIGURE 9 GAS CHROMATOGRAMS OF *SERRIPES GROENLANDICUS* ILLUSTRATING LOW-MOLECULAR-WEIGHT OVERPRINT

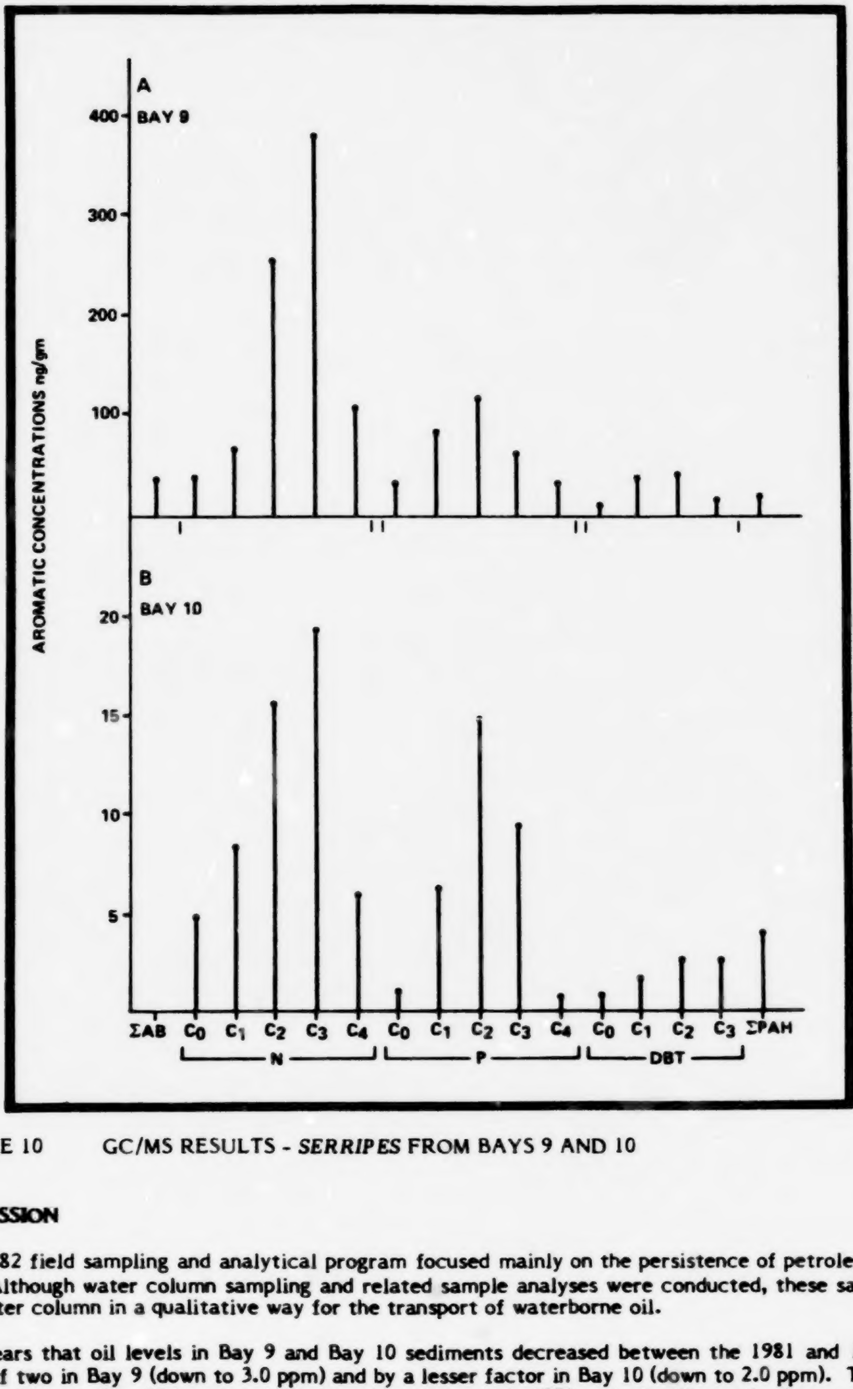

FIGURE 10 GC/MS RESULTS - *SERRIPES* FROM BAYS 9 AND 10

## DISCUSSION

The 1982 field sampling and analytical program focused mainly on the persistence of petroleum residues in the benthic system. Although water column sampling and related sample analyses were conducted, these samples only served to monitor the water column in a qualitative way for the transport of waterborne oil.

It appears that oil levels in Bay 9 and Bay 10 sediments decreased between the 1981 and 1982 samplings by roughly a factor of two in Bay 9 (down to 3.0 ppm) and by a lesser factor in Bay 10 (down to 2.0 ppm). The composition of the low-level oil residues in Bay 10 is quite similar to that observed in 1981. No significant further weathering of the oil is noted in the sediments. This includes weathering through biodegradation. There is no chemical evidence that the microbial population is preferentially using the small amounts of petrogenic n-alkanes in the sediments to any significant extent. Therefore, the biodegradation parameters of ALK/ISO and phytane/n-$C_{18}$ remain constant. Additional physical-chemical weathering is also not significant as the aromatic hydrocarbon composition is still characterized by the occasional presence of alkylated naphthalenes and the definitive alkylated phenanthrene and dibenzothiophene homologous series. Absolute levels of these important aromatic components apparently increased significantly (factor of 2 to 4) from those observed in 1981 in Bay 9 sediments. Levels of the aromatic hydrocarbons quantified (namely the phenanthrenes and dibenzothiophenes) are certainly not decreasing in the sediments.

By far the most dynamic situation vis-a-vis oil transport is seen in Bay 11. After ice breakup (i.e., after May), oil was introduced into the Bay 11 surface water and sediments. Apparently, erosion or tidal flushing of the Bay 11 beach introduced important quantities of oil to the 3 m and 7 m depths. The significant quantities of oil in the surface sediments, 10-70 ppm, had been substantially weathered, although "pockets" of only lightly-to-moderately weathered oil were occasionally observed (i.e., naphthalenes are present). There is ample evidence to postulate that oil had been significantly biodegraded and physicochemically weathered while bound to sediment particles on the beach and subsequently transported to the offshore sediment. There were also significant amounts of oil in the benthic floc layer.

The Bay 7 sediments did contain small quantities (1-2 ppm) of petroleum-type material. When analyzed by $GC^2$ and $GC^2$/MS, it was quite interesting to find the presence of naphthalenes in these sediments and only trace levels of dibenzothiophenes, suggesting that a leachable or water-soluble fraction of some Lago medio source (e.g., Bay 11 beach or Bay 9 beach) had made its way to Bay 7 in small quantities and had been incorporated at low levels into the sediments. The large volume water sample taken in Bay 7 confirms the presence of light petroleum fractions in the water column at low (10-30 ng/L; parts per trillion) levels.

If one takes the entire water volume (0-10 m depth) to be $4.25 \times 10^8$ $m^3$ (Humphrey, personal communication), it would only take 13 kg of these oil components from any source to achieve these water column concentrations. If these components are assumed to be 5% of a suspected source, such as the Bay 11 beached oil, then erosion of 260 kg of oil would yield these levels. This is equivalent to an introduction of merely 0.3 $m^3$ of oil (or 300 L). Therefore, these water column levels could have been achieved by the introduction and mixing of oil from the Bay 11 beach into the Ragged Channel area.

The most powerful set of monitoring measurements relate to the benthic marine organisms. The urchins and *Macoma* (deposit feeders) have been seen to be good sentinels of oil input to sediments. *Mya* and *Serripes* bivalves reflect the waterborne contaminants and *Astarte* appears to reflect both equally well. Absolute concentrations in all animals observed at the end of the 1982 sampling season were much lower than in 1981. On gross concentration levels, oil in the animals was observed to be on the rapid decline to near zero in some species.

Of great interest is the chemical composition of the petrogenic residues in the animals because they tie the water column, sediment, and oil transport data together quite well. Both *Mya* and *Serripes* animals from all of the bays contain a low-molecular-weight n-alkane compositional "overprint" on top of the degraded oil composition seen in these animals in 1981. Note that these low-level "overprints" are only easily seen due to the very low levels of residual oil in these animals. Where concentrations of oil in the animals were greater than 10 ppm or so, these overprints are not detectable. In addition, the homologous series of naphthalenes, apparently eliminated by depuration of oil in the 1981 samples, has been reintroduced at low levels to many of the benthic animals. In September, 1982, subsequent to the appearance of these overprints, the "normal" pattern of degraded oil, the result of in vivo biodegradation in the animals' gut (Boehm et al., 1982a) was observed.

Where are these low-molecular-weight fractions coming from that are observed in the Ragged Channel system? It is possible that oil leaching off the Bay 11 beach could introduce these low-molecular-weight aromatics and alkanes into the system. As little as 300 litres of oil introduced into Bay 11 waters could produce water-soluble material mixed in the water column to yield concentrations of 30 ng/L in all of Ragged Channel. Indeed, 10-50 ng/L were observed in the water samples. Alternatively, and also requiring further study, is the possibility that contamination emanating from groundwater on the Bay 9 beach during and after the dispersed oil release could have occurred. The composition of the Bay 9 beach petroleum residues strongly suggests a water-soluble material in the wet sediment which has the capacity to leach into the system and impact the animals at very low levels. The great efficiency of the animals in concentrating waterborne petroleum had been previously established in the 1981 Bay 7 results (Boehm et al., 1982b). The source of the Bay 9 beach residues is not known. It too, could have come from Bay 11, but the highly unweathered nature of the Bay 9 residues makes this connection quite tenuous.

In conclusion, a number of facts were revealed in the 1982 studies; a number of hypotheses are suggested by the data.

## CONCLUSIONS

a) Biodegraded, physicochemically weathered oil was eroded from the Bay 11 beach and impacted the 3 m and 7 m sediments and floc.

b) There is no evidence for the occurrence of biodegradation of oil in offshore sediments.

c) There is evidence for only minimal vertical mixing of oil into the sediment column.

d) There is evidence for the occurrence of low levels of low-molecular-weight aromatics and saturates in the water column of Ragged Channel.

e) Filter-feeding bivalves have depurated most of their petroleum body burdens, but are left with a low-molecular-weight saturate and aromatic hydrocarbon "overprint".

f) Deposit-feeding animals are much lower in oil concentration than in 1981, but still have 20-60 ppm of petrogenic residues.

### Hypothesis

a) Oil in Bay 9 or Bay 11 beach/groundwater was/is a source of low-level petroleum contamination to the water column and, hence, to the animals.

b) Oil leaching off the Bay 11 beach is affecting the chemistry of the entire Ragged Channel area.

c) Oil will continue to increase in concentration in Bay 11 sediments, with the possibility of offshore (deeper) transport and vertical penetration into the sediment increasing with time.

d) The opportunity for biodegradation to occur in Bay 11 sediments will increase as oil concentrations increase.

## ACKNOWLEDGEMENTS

The BIOS project is a team effort involving a management committee of government and industry scientists, technical committees for each of the disciplines, and participating scientists. The author would like to especially thank all those involved in the difficult sample collection efforts for their invaluable assistance in this project.

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# BIOS PROJECT - PRELIMINARY RESULTS

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## INTRODUCTION

The Baffin Island Oil Spill (BIOS) Project, formally initiated in March 1980, is now entering the fourth and final year of the planned field work. The primary objectives of this internationally funded project are: a) to determine if the use of chemical dispersants in the Arctic nearshore will reduce or increase the environmental effects of spilled oil; b) to assess the fate of oil; and c) to compare the relative effectiveness of other shoreline protection and cleanup techniques.

This article only touches on the more significant and interesting preliminary results of the BIOS Project. The considerable quantity of data produced during the first 3 years of study can be found in the Project's working reports. These are published annually and can be obtained from the office of the authors of this paper. Reference to the Shoreline Countermeasures Study (objective c above) has been omitted as the results are presented in these Proceedings by Dr. E.H. Owens.

## EXPERIMENTAL OIL RELEASES

Prior to addressing the preliminary results, it is worthwhile to quickly review the experimental oil releases.

### Surface Oil Release

On August 19, 1981, oil was released onto the surface waters of Bay 11 (Figure 1). As planned, the release began at high tide and lasted for 6 hours. A total of 15 $m^3$ of aged crude oil were discharged under the influence of a westerly wind which carried the surface oil slick to the shoreline, where it was subsequently stranded as the tide fell. The result was an even coating of oil across the whole intertidal zone along the 200 m long test section of coastline.

### Dispersed Oil Release

On August 27, 1981, dispersant-treated oil was released into Bay 9. Similar to the untreated surface oil release, the discharge began at high tide and lasted for a period of 6 hours. A total of 15 $m^3$ of aged crude oil, 1.5 $m^3$ of the dispersant Corexit 9527 and 75 $m^3$ of seawater were premixed in the discharge pipe prior to release through the subsea diffuser system. The dispersed oil cloud moved through the study areas of Bay 9 and Bay 10 and subsequently spread throughout the top 10-15 m of Ragged Channel.

## RESULTS

### Dispersed Oil Release

Perhaps the most dramatic results were the initial responses of various benthic organisms to the dispersed oil, both in Bay 9 where the release took place (average exposure 300 ppm-h, average maximum 50 ppm) and in Bay 10 (average exposure 300 ppm-h and average maximum 5 ppm), which received an exposure approximately an order of magnitude lower. Shortly after the oil release, divers observed numerous individuals of various species in abnormal postures and locations. Infauna such as bivalves and polychaetes emerged from their normal environment just below the sediment surface. These animals, along with others such as star fish and urchins, were in unnatural postures (e.g., gaping, upside down) and had little response to prodding. Within 2 weeks, the majority of the stressed animals appeared to regain normal functions. The "surfaced" infauna such as the polychaetes and bivalves appeared to have reburied. Although there were visual observations of predation on affected animals (by urchins and star fish), massive predation of the exposed organisms has since been ruled out. This is not surprising as primary predators (sea mammals and birds) are not abundant in the area. However, in an area where predators were abundant, the exposed organisms would have been very vulnerable; an acceleration of hydrocarbons up the food chain would therefore have been possible.

In support of the observed recovery, the systematic monitoring of benthic populations has demonstrated that the exposure to dispersed oil did not cause large-scale mortality of benthic animals. Even after 1 year, there were no statistically significant changes measured in benthic community composition. Although some possible long-term effects on selected species are indicated, the significance and certainty of such trends have yet to be ascertained.

Chemical analysis of the tissue of five species of benthic animals in Bays 9 and 10 revealed that significant concentrations of oil were accumulated and depurated over the 12-month post-spill monitoring period. Filter feeding bivalves (e.g., *Mya truncata* and *Serripes groenlandicus*) rapidly accumulated high quantities of waterborne oil. As an example, concentrations of 100-500 μg/g (dry weight) were attained within 2 days following the release. Subsequent monitoring at 2 weeks post-spill revealed that body burdens were declining; after 1 year, they were down to a range

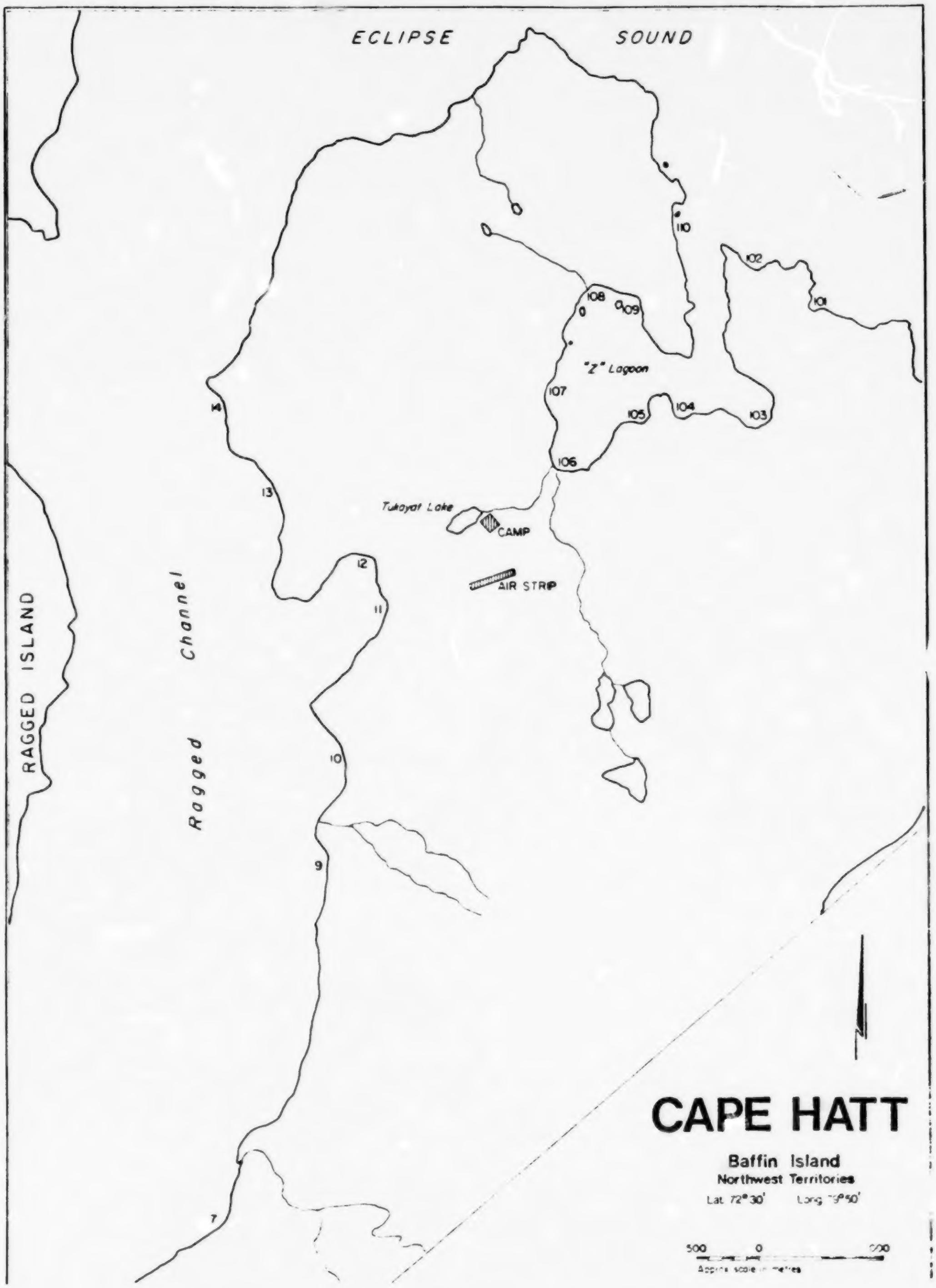

ECLIPSE SOUND
RAGGED ISLAND
Ragged Channel
"Z" Lagoon
Tukoyat Lake
CAMP
AIR STRIP
7
9
10
11
12
13
14
101
102
103
104
105
106
107
108
109
110
CAPE HATT
Baffin Island
Northwest Territories
Lat. 72° 30'
Long. 79° 50'
500
0
Approx. scale in metres

FIGURE 1 CAPE HATT (Baffin Island, Northwest Territories)

between 1 and 5 µg/g. A slightly different trend was monitored in the deposit feeders such as the urchin (*Strongylocentrotus droebachiensis*) and a bivalve (*Macoma calcarea*). Although these animals accumulated initial waterborne oil, the concentrations of oil in their tissue continued to increase due to continued ingestion of contaminated material. At 1 year post-spill, significant depuration had occurred; nevertheless, these concentrations still exceeded those in the filter feeders. Despite the high body burdens in all species, no massive mortality has been monitored. It remains to be seen whether or not any significant sublethal effects (such as on reproduction) will result.

The lack of correlation between the concentrations of oil in the tissues of the benthic organisms and the exposure to dispersed oil is of interest. For example, in Bay 10, tissue levels in some organisms exceeded those of their counterparts in Bay 9 despite the order of magnitude difference in exposure. Other examples were in Bays 7 and 11 which, several days following the dispersed oil release, received very low levels (e.g., 1 ppm-h, maximum 10-100 ppb) of the then widely dispersed oil. In some cases, tissue hydrocarbon levels in Bay 7 reached those monitored in Bays 9 and 10 despite several orders of magnitude difference in exposure. A possible explanation for this lack of correlation is that the high oil concentrations retarded normal body functions (such as by narcosis) and reduced, for example, the rates of filtration in the bivalves of Bays 9 and 10, while the bivalves in Bay 7 experienced such low levels that their normal filtration rate was less affected.

Thought has been given to the fact that perhaps greater exposures to dispersed oil were experienced in Bays 7 and 11 than was monitored in the water column. This, however, is considered unlikely due to the sediment hydrocarbon levels measured. The high concentrations of dispersed oil did contaminate the bottom sediments, and the level of contamination was related to exposure. In Bay 9, average sediment hydrocarbon levels monitored following the release were approximately 5 µg/g; in Bay 10 they were 1.5 µg/g; and only small traces of oil were detected in Bay 7 despite sophisticated analytical techniques (GC, GC/MS). At 1 year post-spill, the average sediment values in Bays 9 and 10 had declined; however, oil was still present.

### Surface Oil Release

Contrary to the results of the dispersed oil release, the untreated surface oil release in Bay 11 had no immediate effects on the local subtidal benthic organisms. There was some physical oiling of amphipods in the intertidal zone, but otherwise nothing was observed. This was not surprising because oil concentrations in the water column below the experimental slick were low (maximum 2.8 ppm) and only detectable in the upper 1 m of the water column; significant concentrations of benthic organisms are not found above the 3 m bathymetric contour. Sampling of the benthic populations 1 year post-spill has revealed no significant changes in community composition. Similar to Bays 9 and 10, the data suggest possible species-specific chronic effects.

Two days following the surface oil release (and prior to the influence of any dispersed oil), significant amounts of oil had accumulated in the tissues of benthic organisms monitored in Bay 11. For example, the filter feeding bivalve *Mya truncata* increased from an average background level of 0.43 µg/g to 3.3 µg/g (dry weight), and the surface deposit feeding bivalve *Macoma calcarea* increased from 0.50 to 2.7 µg/g. Body burdens, measured again some 3 weeks post-spill, had increased significantly. Although influenced by the dispersed oil release by this time, the tissue levels in organisms in Bay 11 were all higher than in Bay 7.

Monitoring of tissue hydrocarbon levels in Bay 11, 1 year following the release, revealed that body burdens of oil had been reduced. However, in all monitored organisms, the tissue hydrocarbon levels in Bay 11 were at least as high or higher than those in the dispersed-oil test Bays 9 and 10. The animals with the highest concentrations remaining in their tissues were the deposit feeders.

The trend towards higher tissue hydrocarbon levels in Bay 11 correlates well with the observed subtidal sediment hydrocarbon levels. Opposite to the trends in Bays 9 and 10, the sediment hydrocarbon levels in Bay 11 increased during the year following the oil releases. The average sediment concentration at the completion of the 1981 sampling program in Bay 11 was 1.10 µg/g. However, the average concentration monitored during the summer of 1982 was 8 µg/g, with the actual levels ranging from less than 1 µg/g to over 60 µg/g. This heterogeneity was caused by selective deposition of particulate oil leaching from the contaminated intertidal zone.

Sampling of the oiled intertidal zone in Bay 11 immediately following the untreated oil release revealed that over 7 $m^3$ of oil had been stranded. A similar sampling program in 1982 concluded that over 5 $m^3$ of oil still remained. These results demonstrated that there is still a potential for further elevation or at least continued input of oil into the subtidal sediments and animal tissues of Bay 11.

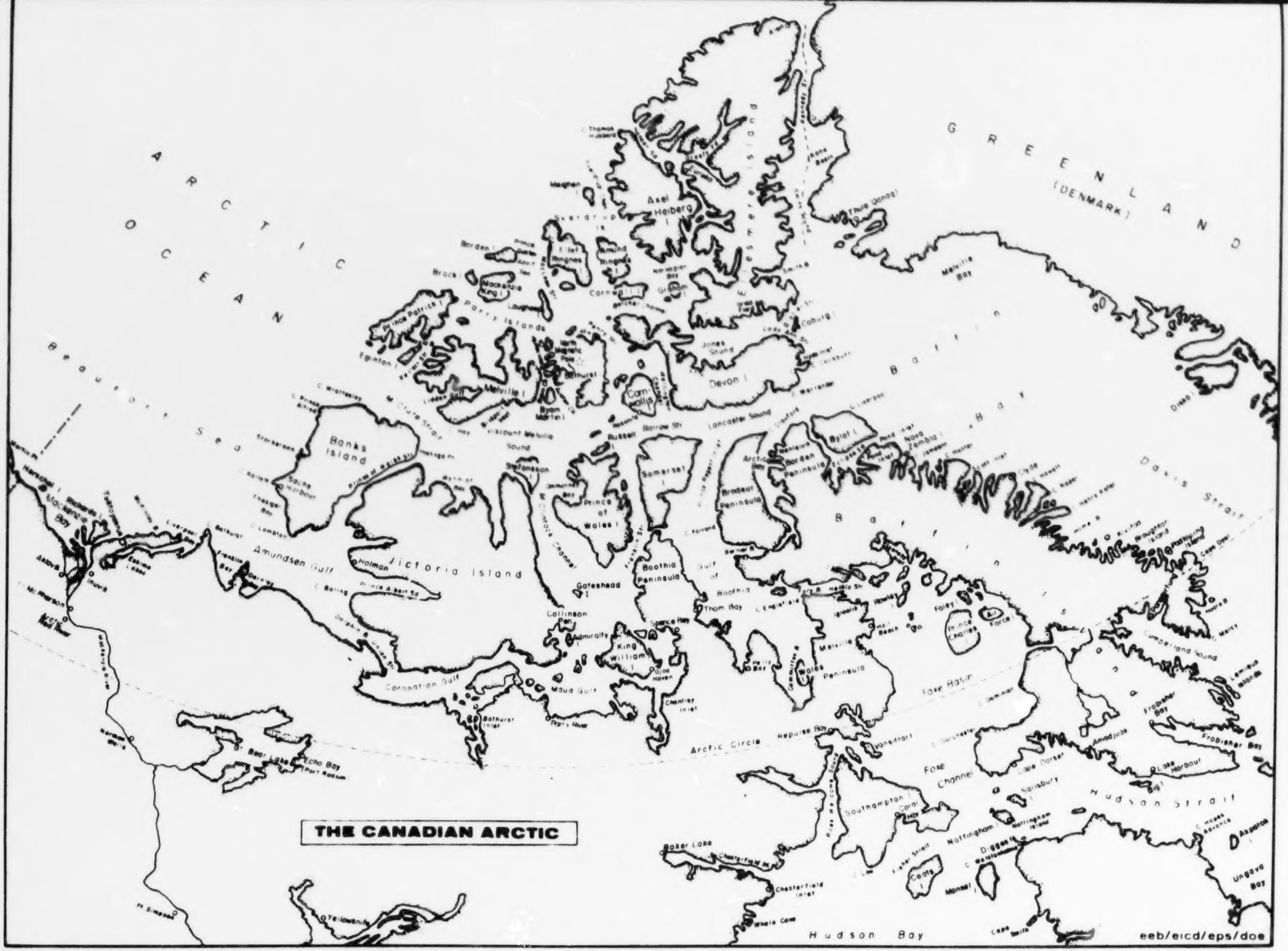
### SUMMARY

Analysis of the BIOS Project's preliminary results has led to the conclusion that neither the dispersant-treated nor the untreated surface oil release had any acute environmental effects. The ultimate impact of both releases is, however, still unknown. The continued movement of oil from the Bay 11 beach to the subtidal sediments may eventually result in significant impacts on the benthic community. Also, it is possible that the dispersant-treated oil may have had longer-term sublethal effects. As an example, a major reduction in reproductive capability could become important over time.

The fourth-year field program of the BIOS Project will firmly establish the significance of the trends discussed above. Further, these results will be valuable in making predictions about the appropriateness of returning to Cape Hatt in the future to monitor the longer-term fate, behaviour, and effects of the experimental oil releases.

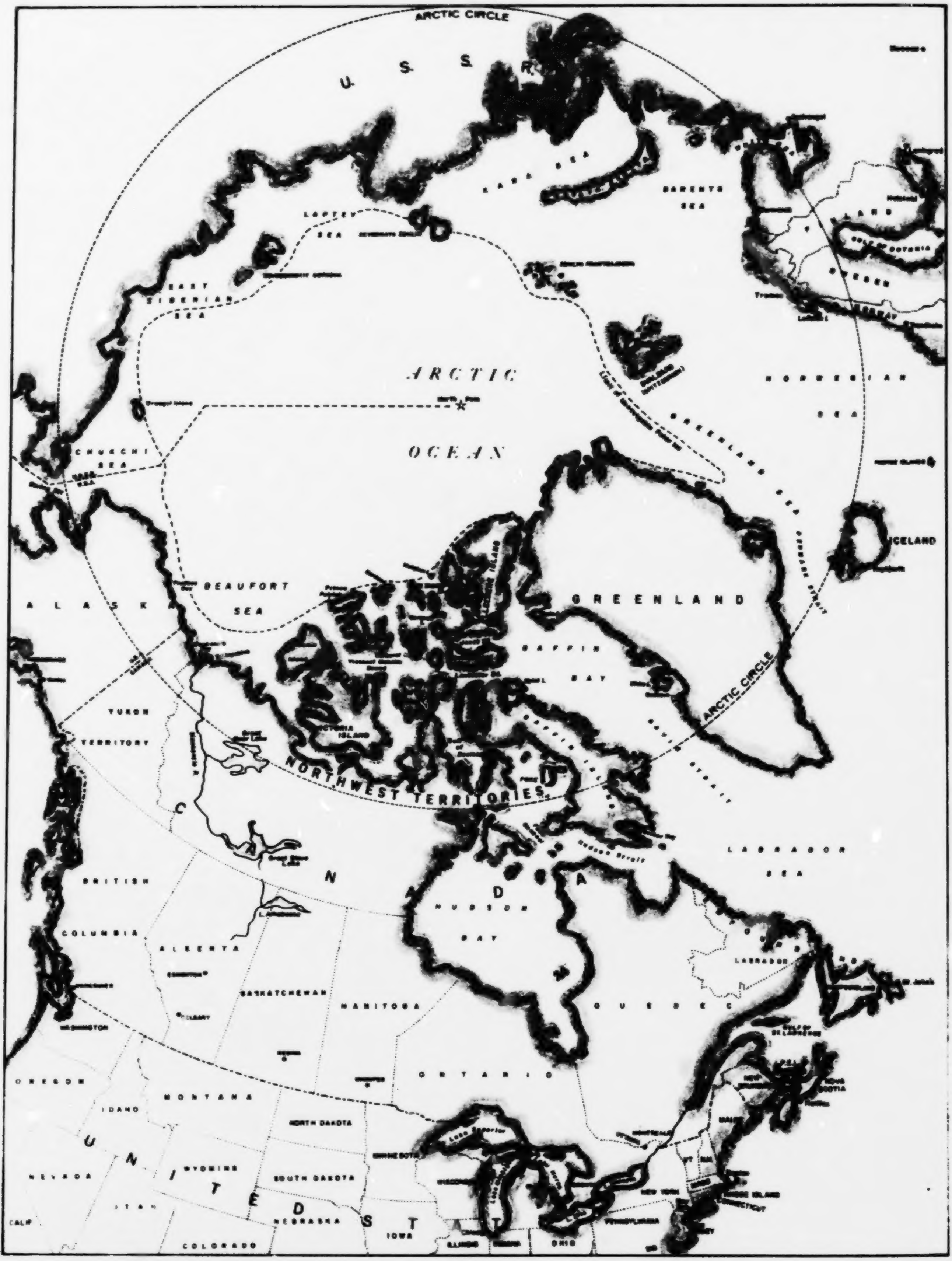
## ACKNOWLEDGEMENTS

The BIOS Project is funded by the Canadian Federal Government, the Canadian Offshore Oil Spill Research Association (COOSRA), the Outer Continental Shelf Environmental Assessment Program (OCSEAP), the United States Coast Guard (USCG), the Norwegian Government, and British Petroleum International. The continued support of these agencies and, in particular, their representatives on the Project management committee is greatly appreciated. Special thanks are extended to the many scientists, engineers and technicians who have worked hard to make the BIOS Project a success.


ARCTIC OCEAN
Beaufort Sea
GREENLAND
(DENMARK)
Baffin Bay
Davis Strait
Baffin Island
Ellesmere Island
Axel Heiberg I
C Thomas Hubbard
Meighen I
Sverdrup Is
Ellef Ringnes I
Amund Ringnes I
Borden I
Prince Patrick I
Brock I
Mackenzie King I
Lougheed I
Parry Islands
Eglinton I
Melville I
North Magnetic Pole
Bathurst I
Byam Martin I
Cornwall I
Graham I
Norwegian Bay
Belcher Channel
Cornwallis I
Wellington Channel
Devon I
Jones Sound
Coburg I
Lady Ann Str
C Sherard
C Warrender
Smith Sd
Kane Basin
Kennedy Ch
Alert
Eureka
Thule (Qanaq)
Melville Bay
Disko I
C Wrottesley
C Prince Alfred
M'Clure Strait
Banks Island
Sachs Harbour
Storkerson
Thesiger Bay
C Lambton
C Bathurst
Prince of Wales Str
Viscount Melville Sound
Stefansson I
Resolute
Barrow Str
Lancaster Sound
Russell I
Somerset I
Prince of Wales I
M'Clintock Channel
Franklin Str
Prince Regent Inlet
Bylot I
Pond Inlet
Nova Zembla I
C Crauford
Arctic Bay
Borden Peninsula
Brodeur Peninsula
Eclipse Sd
C Hunter
Scott Inlet
Clyde
Home B
Kivitoo
Broughton Island
Padloping Island
Cape Dyer
Hall B
C Mercy
Cumberland Sound
Lemieux Islands
Frobisher Bay
Lake Harbour
Big I
Hudson Strait
Akpatok I
Ungava Bay
C Hopes Advance
Amadjuak
Cape Dorset
Salisbury I
Nottingham I
Nottingham Island
Diggees I
C Wolstenholme
Mansel I
Coats I
Fisher Strait
Southampton I
Coral Hbr
Roes Welcome Sound
Foxe Channel
Foxe Basin
Prince Charles I
Air Force I
Foley I
Rowley I
Hall Beach
Igloolik
Fury & Hecla Str
Melville Peninsula
Committee B
Wales I
Pelly Bay
Repulse Bay
Vansittart I
C Dorchester
C Dominion
Arctic Circle
Gulf of Boothia
Boothia Peninsula
Thom Bay
C Englefield
C Farrand
Berner B
Gateshead I
Collinson Pen
Admiralty I
King William I
Gjoa Haven
Spence Bay
Chantrey Inlet
Maud Gulf
Perry River
Bathurst Inlet
Coronation Gulf
Dolphin & Union Str
Victoria Island
Holman
Prince Albert Sd
C Baring
Amundsen Gulf
Franklin Bay
Paulatuk
C Parry
Mackenzie Bay
Herschel I
Richards I
Tuktoyaktuk
Eskimo Lakes
Inuvik
Aklavik
Ft McPherson
Arctic Red River
Mackenzie River
Norman Wells
Gr. Bear Lake
Echo Bay
(Port Radium)
Ft Simpson
Yellowknife
Baker Lake
Chesterfield Inlet
Whale Cove
Cape Smith
Hudson Bay

**THE CANADIAN ARCTIC**

eeb/eicd/eps/doe


ARCTIC CIRCLE
U. S. S. R.
KARA SEA
BARENTS SEA
LAPTEV SEA
EAST SIBERIAN SEA
ARCTIC OCEAN
North Pole
CHUKCHI SEA
BEAUFORT SEA
ALASKA
GULF OF BOTHNIA
SWEDEN
NORWAY
Tromsø
NORWEGIAN SEA
GREENLAND SEA
ICELAND
GREENLAND
BAFFIN BAY
ARCTIC CIRCLE
DAVIS STRAIT
BAFFIN ISLAND
Hudson Strait
LABRADOR SEA
VICTORIA ISLAND
NORTHWEST TERRITORIES
YUKON TERRITORY
CANADA
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
QUEBEC
HUDSON BAY
LABRADOR
NEWFOUNDLAND
GULF OF ST. LAWRENCE
NOVA SCOTIA
WASHINGTON
OREGON
IDAHO
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
WYOMING
NEVADA
UTAH
CALIF.
COLORADO
NEBRASKA
IOWA
MINNESOTA
Lake Superior
MONTREAL
VT
NH
MAINE
NEW YORK
RHODE ISLAND
PENNSYLVANIA
OHIO
UNITED STATES

POOR

QUALITY

ORIGINAL